# GEOLOGY OF THE MISSISSIPPI RIVER DELTAIC PLAIN SOUTHEASTERN LOUISIANA

TECHNICAL REPORT NO. 3-483

Volume I

July 1958

U. S. Army Engineer Waterways Experiment Station
CORPS OF ENGINEERS
Vicksburg, Mississippi

U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss. GEOLOGY OF THE MISSISSIPPI RIVER DELTAIC PLAIN, SOUTHEASTERN LOUISIANA, by C. R. Kolb and J. R. Van Lopik. July 1958, 120 pp - illus - tables. (Technical Report No. 3-483, 2 volumes)

Unclassified report

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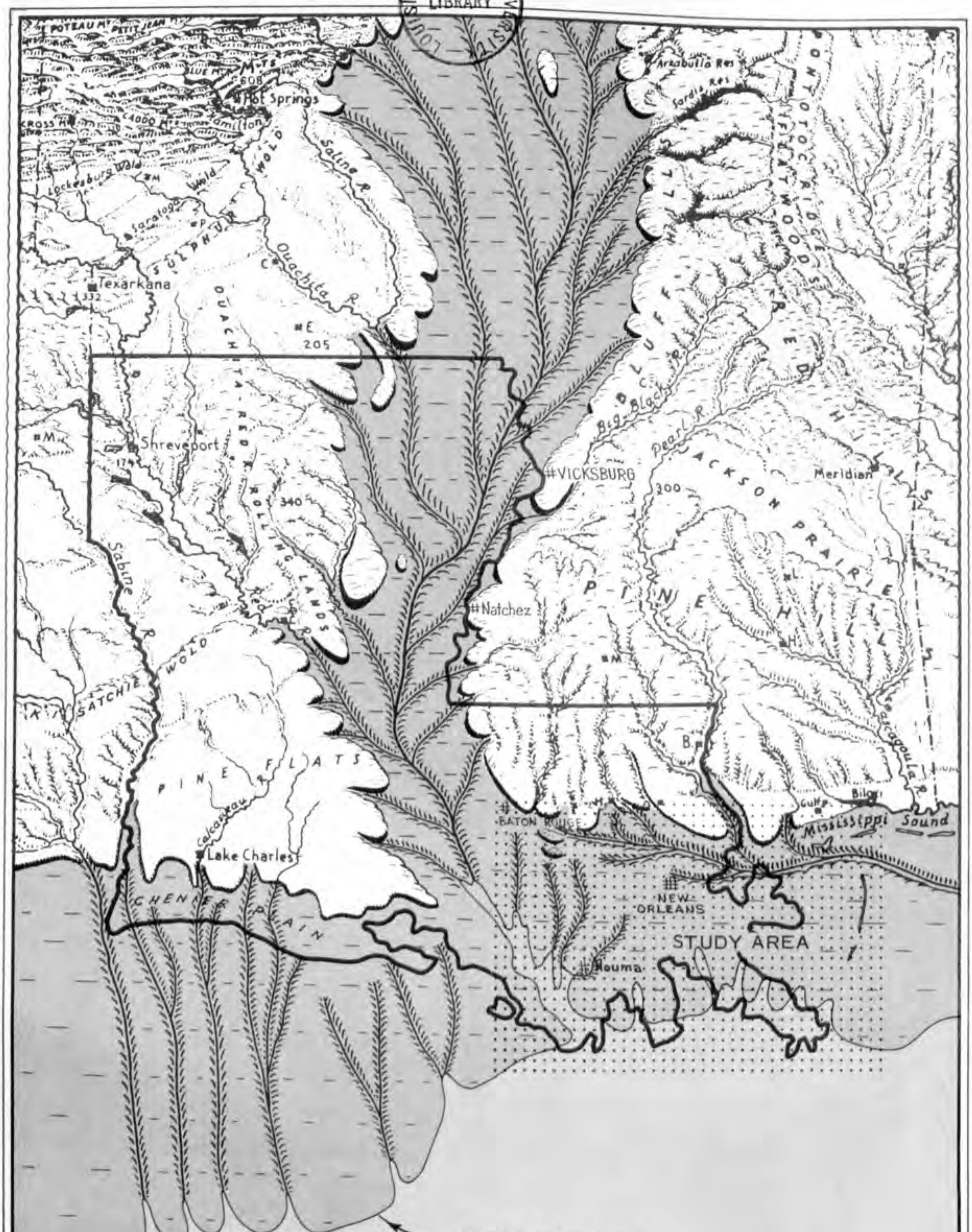


Frontispiece. Mississippi Valley during the Ice Age

Dor Cell



# PREFACE

This study was authorized by a letter from the Division Engineer, U. S. Army Engineer Division, Lower Mississippi Valley, to the Director, U. S. Army Engineer Waterways Experiment Station, subject, "Projects for the Geology Branch, Soils Division, Fiscal Year 1955," dated 31 August 1954. Publication of this report, originally scheduled for June 1957, was postponed in order that boring information obtained for the proposed Mississippi River-Gulf Outlet Channel might be included in the study. Miscellaneous Paper No. 3-259, Geological Investigation of the Mississippi River-Gulf Outlet Channel, was published in February 1958.

Plates accompanying the report were prepared by Mr. Charles R. Kolb, Dr. J. R. Van Lopik, Messrs. W. B. Steinriede, Jr., P. R. Mabrey, R. D. Fitler, Harry K. Woods, and Mrs. J. J. McLeskey, Jr., Geology Branch, Soils Division. The report was written by Mr. Kolb and Dr. Van Lopik. The study was accomplished under the direct supervision of Mr. Kolb and the general supervision of Mr. W. J. Turnbull, Chief of the Soils Division, U. S. Army Engineer Waterways Experiment Station.

Acknowledgment is made to the following organizations and individuals for their courtesy in furnishing information utilized in this study: Atlantic Refining Company; The California Company; Gulf Refining Company; Humble Oil & Refining Company; Shell Oil Company; Pan American Oil and Gas Company; Sun Oil Company; Union Producing Company; Louisiana State Highway Department; Louisiana Wild Life and Fisheries Commission; Coastal Studies Institute of Louisiana State University; Palmer and Baker, Consulting Engineers; Eustis Engineering Company, Consulting Engineers; Dr. H. N. Fisk and Mr. E. McFarlan, Jr., Geologic Research, Humble Oil and Refining Company; Dr. H. A. Bernard, Shell Development Company; Dr. R. C. Treadwell, Pan American Oil and Gas Company; Professor E. W. Orton, Louisiana Polytechnic Institute.

The writers wish to express their appreciation of the critical review of the draft of this report and helpful suggestions made by Mr. W. G. Shockley, Soils Division, USAEWES, Mr. Robert Kaufman, USAEDLMV, and Mr. Herman Huesmann, USAE District, New Orleans.

# CONTENTS

## SUMMARY


Environments of Recent deposition of the deltaic plain of the Mississippi River are classified from the standpoint of their associated engineering soil types as follows:

Fluvial

- natural levee
- point bar
- abandoned course
- abandoned distributary

Fluvial-marine

- prodelta
- intradelta
- interdistributary

Paludal

- marsh
  - saline-brackish
  - brackish-fresh
  - flotant
  - fresh
- swamp
  - inland
  - mangrove
- tidal channel
- lacustrine

Marine

- bay-sound
- reef
- beach
  - sand
  - shell
- nearshore gulf

The processes active within each environment, the soil types associated with each, their distribution, and their physical properties are described, graphically illustrated, and/or delineated on maps. The sequence of geologic events that shaped the deltaic plain is outlined.

Subsidence, an important factor in deltaic plain morphology, is discussed. It varies from more than 5 ft per century within the present Mississippi River Delta to less than 2 ft per century at the shore line of the remainder of southeast Louisiana.

# GEOLOGY OF THE MISSISSIPPI RIVER DELTAIC PLAIN SOUTHEASTERN LOUISIANA

## PART I: INTRODUCTION

1. One of the regions intensively studied by geologists during the past 10 years is the Mississippi River deltaic plain and its associated offshore area. Impetus for these studies was primarily provided by oil companies eager to exploit the petroleum resources of the shallow continental shelf. Basically the investigations were directed toward correlation of deposits found within the Mississippi deltaic plain with similar ancient sediments of the geologic column; research aimed at predicting, through examination of rock cores taken thousands of feet below the surface, the lateral distribution and thickness variations of deltaic deposits at great depths. Within the last 10 years the American Petroleum Institute and the major oil companies have spent millions of research dollars in the delta area. Extensive studies have also been made in the delta by the Coastal Studies Institute of Louisiana State University under the auspices of the Office of Naval Research. Accelerated construction and oil exploration programs have provided much data concerning the properties of various deltaic deposits that relate to their suitability as foundations for buildings, causeways, bridges, drilling platforms, etc.

2. The purpose of this report is to consolidate data gathered by the Corps of Engineers in various geologic investigations, and to augment this material with pertinent information garnered from the extensive investigations and studies mentioned in the preceding paragraph. Although an attempt has been made to discuss all environments of deltaic deposition, attention is focused on those deposits which, because of their unique physical characteristics, are most important from an engineering standpoint.

3. Significant advances have been made in correlating engineering soil types with geologic environments in the northern part of the Mississippi Alluvial Valley. From Cairo southward to the latitude of Baton

Rouge, air photographs and a knowledge of the geologic processes can be used to accurately predict soil types* and the lateral distribution of these types within the flood plain, both at the surface and at shallow depth. Detailed boring programs intended to refine and quantify these predictions can be more logically planned and economically executed by taking maximum advantage of preliminary airphoto delineation of soil types. South of Baton Rouge, however, a significant change occurs in the depositional processes which makes aerial photographs less useful for soil identification. While upstream deposition is solely alluvial or fluvial, the deltaic mass of southern Louisiana has been modified by marine processes. In the deltaic plain, depositional types are often masked by vegetation or water, and relief is almost nonexistent, so that delineation of soil types by airphoto interpretation becomes exceedingly difficult. In addition, geologists and sedimentologists are only partially agreed on the various processes that build, and the environments that typify, the deltaic plain. Nevertheless, the engineer is in need of reasonable classification of deltaic environments that will aid in interpreting the rapidly increasing number of soil borings spawned by the accelerated cultural development of the delta area during the past decade.

4. The present study proposes to: (a) briefly outline the physiography and geologic history of the Mississippi River deltaic plain; (b) classify and describe the major environments of deposition; (c) map the distribution of these environments, and the types of materials that compose them, in southeastern Louisiana; (d) summarize available data on the engineering properties of deltaic deposits; and (e) discuss briefly the closely related and omnipresent factor of subsidence.

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* Soil, as an engineering term, may be defined as a naturally occurring accumulation of uncemented, or loosely cemented, inorganic and/or organic materials.

## PART II: PHYSIOGRAPHY AND GEOLOGIC HISTORY

5. The coast of Louisiana is fringed by a band of marshland 10 to 80 miles in width (see plate 1). The western, narrower band of marsh--the chenier plain of southwest Louisiana--is characterized by stranded, marsh-surrounded beaches or cheniers (see frontispiece). Gulfward-projecting, natural levee ridges bordering active and abandoned courses and distributaries of the Mississippi River typify the eastern marshes. This eastern region, which spans almost 200 miles of coastal Louisiana--from Vermilion Bay (about longitude 92°W) to the Chandeleur Islands (fig.1)--comprises the deltaic plain of the Mississippi River. The plain encompasses the active and abandoned deltas of the Mississippi River and forms a distinct physiographic unit, bounded on the west by the chenier plain of southwest Louisiana; on the east and south by the Gulf of Mexico; and on the north by (a) the relatively distinct contact with older, gulfward-dipping Pleistocene deposits, and (b) a rather arbitrary line marking the southern limit of the Lower Mississippi Alluvial Valley flood plain deposits.

6. Natural levees, created by near-channel deposition of suspended sediment during overbank flow, form the framework of the region. In the northern portion of the deltaic plain, natural levees along the present Mississippi reach elevations of 25 to 27 ft msl and average two to three miles in width; near New Orleans the average elevation is approximately 10 ft and widths average one mile; farther downstream at Empire, Louisiana (29°25'N, 89°35'W), the average elevation is 5 ft and widths are typically 1000 or 2000 ft. Natural levee elevations along the central portions of Bayou Lafourche and Bayou La Loutre approximate 12 and 8 ft, respectively. Between the low double-crested ridges formed by the natural levees, basins of marsh and swamp are found. In the more interior basins, woody swamplands predominate and surface elevations of 2 to 4 ft occur. Toward the gulf the lows are occupied by marsh sedges and grasses and the general surface elevation approximates mean high tide, i.e., 1.2 ft. Beaches, typically 1 to 10 ft in elevation and of varying width, discontinuously rim the gulfward margin of the deltaic plain.

7. To appreciate the evolution of this surface the geologic clock must be turned back 20,000 years. The configuration and terrain of eastern

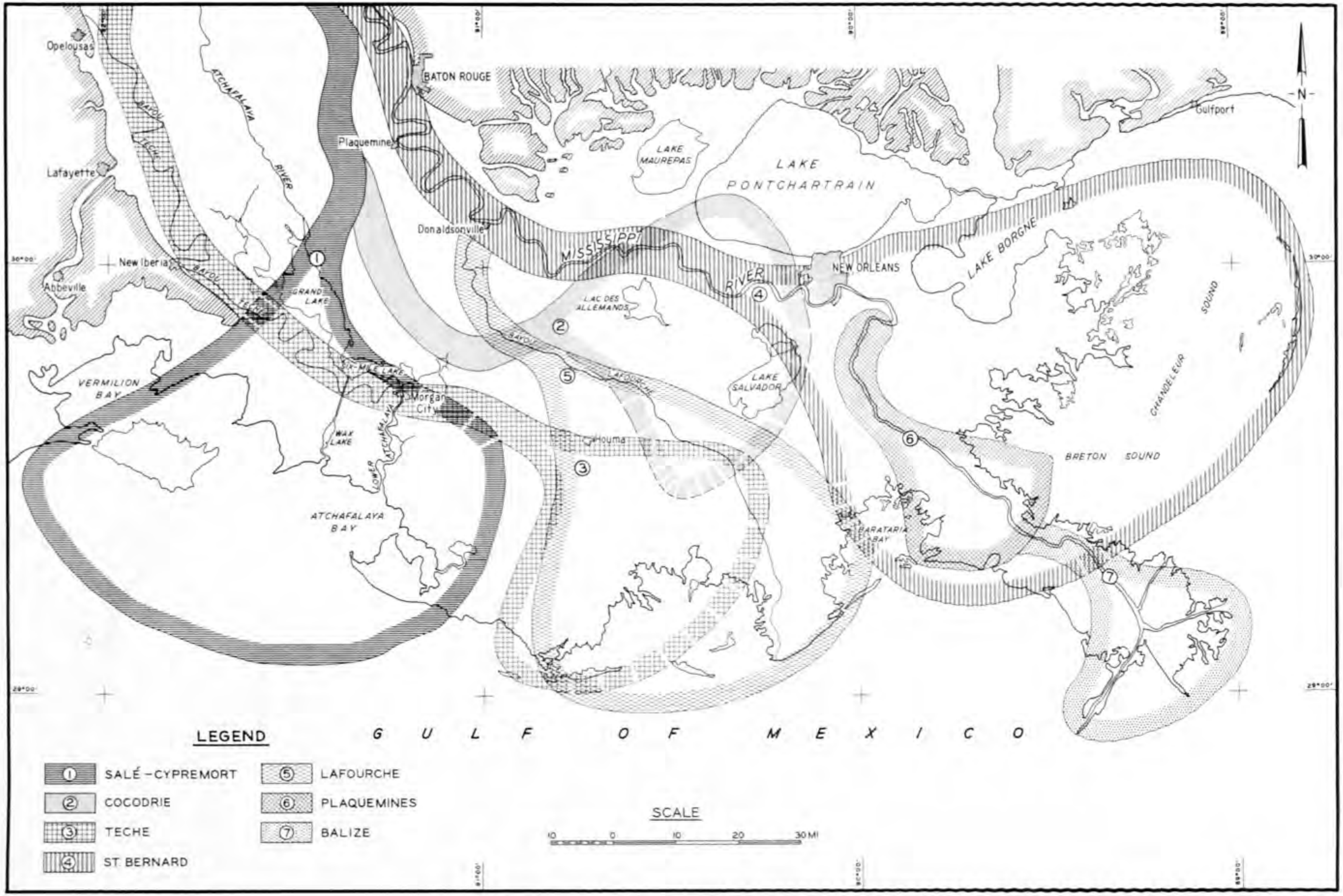


Fig. 1. Mississippi River deltas

coastal Louisiana at that time (the Pleistocene surface) differed markedly from that of its modern counterpart. Sea level was some 400 ft below its present stand and, as a result, the shore line was located, for the most part, far gulfward of its present position (see frontispiece). The lowering of sea level, in response to an accelerated amassment of glacial ice in the polar regions, led to entrenchment of the gulfward-flowing streams and their tributaries. The master stream, the ancestral Mississippi, formed a wide valley, 10 to 25 miles across, with gently sloping sides. This shallow entrenchment, which exhibited axial depths in excess of 400 ft, trended southeasterly across the coastal area approximately 15 miles west of the site of Houma, Louisiana (see plate 1 for identification of place names). Branching tributaries of the master valley formed a drainage basin 60 to 100 miles in width. Smaller drainage basins, whose major streams entered the gulf directly, were also formed.

8. Today, some very narrow zones along the immediate valley edges are characterized by steep slopes which rise a maximum of 100 ft above the entrenched valley floor. However, the width-depth relationship of most entrenchments is such that the valley-floor slopes are quite gentle, i.e., less than 2 degrees (approximately 3.5 per cent or 180 ft per mile).* Consequently, although the axial portion of the master entrenchment lies more than 400 ft below the level of the flanking interfluves--and central and headward portions of major tributary valleys often exhibit axial depths of 100 or 200 ft--local relief within the entrenchment and the flanking interfluve can be consistently measured in tens of feet.

9. Between 17,000 and 15,000 years ago sea level began to rise--a result of glacial melting initiated by climatic amelioration. Regional subsidence of the coastal area further augmented this rise. Streams, in an attempt to adjust to the rise in base level, alluviated their shallow entrenched valleys. Although clays, silts, and fine sands were still

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* Such inclinations correspond with those exhibited by the bajadas or alluvial aprons of existing world desert areas. Nevertheless, these gentle slopes seem rather precipitous compared to those found in coastal Louisiana today, e.g., the back slopes of Mississippi River natural levees average less than 10 ft per mile, the longitudinal slope of the Mississippi River natural levee crests from Baton Rouge to the gulf is approximately 0.15 ft per mile.

transported to the gulf and deposited considerable distances off- and alongshore, coarse sands and gravels were now dropped near the mouth of the master entrenchment. When deposition could not keep pace with sea-level rise, the sandy deltas were forced farther upvalley, forming a coarse basal layer of fluvial sediments overlain--in the distal portions of the valley--by estuarine-marine deposits. The rising sea transgressed and slightly planated the low-lying interfluves, creating a discontinuous blanket of beach or strand and nearshore gulf sediments, supplied through alongshore drifting of delta sands and reworking of the older sandy delta and Pleistocene deposits.

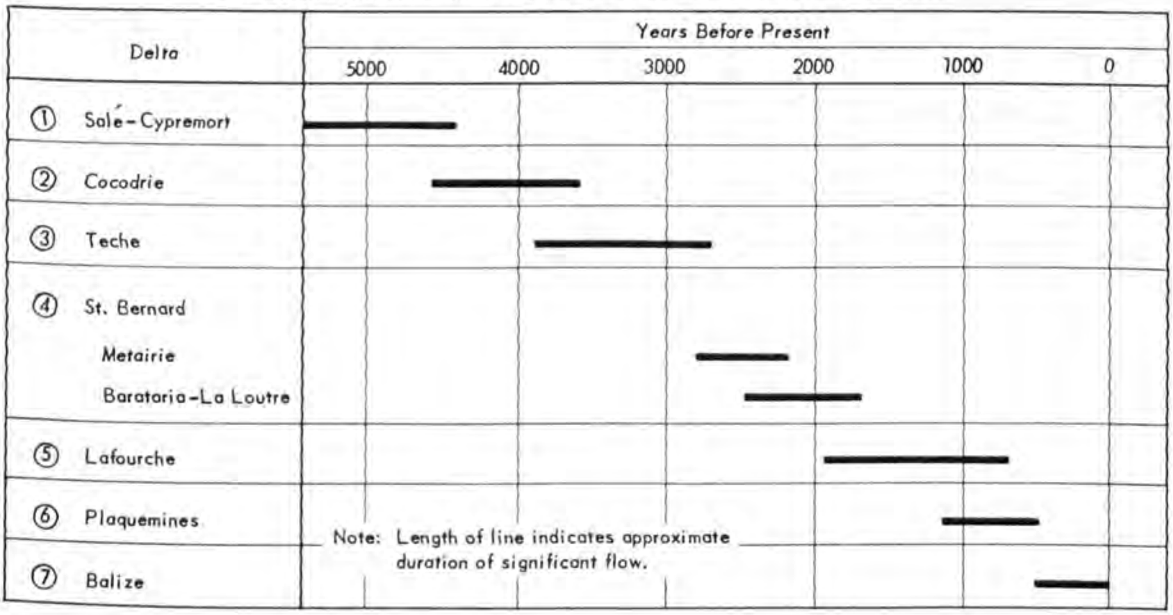
10. As sea level continued to rise both the quantity and the grain size of detritus supplied the streams were diminished; the alluvium deposited in the valleys became progressively finer grained and the rate of valley alluviation decreased. The site of sand deposition rapidly shifted upvalley, and the deltas received only fine sands, silts, and clays.

11. Five to seven thousand years ago the rise in sea level ceased. Lobate deltas were formed, displacing the gulf waters which extended up the Mississippi Alluvial Valley to the latitude of Baton Rouge, Louisiana. This gulfward growth was accompanied by many shifts in the locations of the various Mississippi River courses and their associated deltas. A front of fine-grained alluvium advanced gulfward over the subsided, filled, and buried valleys and interfluves. This material was deposited over the valley sequence of thick basal fluvial sands--covered by thin deposits of estuarine-marine and older fine-grained alluvium--and over the beach or strand and nearshore gulf sediments capping the intervalley highs.

12. Several major delta complexes, formed during the last 5000 years and reflecting significant changes in the course of the Mississippi River, are discernible in coastal Louisiana. From oldest to youngest the delta complexes (see fig. 1) are: Salé-Cypremort, Cocodrie, Teche, St. Bernard, Lafourche, Plaquemines, and the present Balize. The St. Bernard complex consists of two fairly distinct segments or lobes: an early partial-flow course in the north, the Metairie segment; and a later full-flow course in the south, the Barataria-aux Chenes-La Loutre complex. During the occupation of the Metairie course a large portion of Mississippi flow was directed into the Grand River Basin area, north of the Teche ridge. While the time

**Table 1**

APPROXIMATE AGE OF DISCERNIBLE MISSISSIPPI RIVER DELTAS




sequence or relative ages of the delta complexes are well-established, their absolute ages are less certain. The approximate ages presented in table 1 are based, wherever possible, on Carbon-14* data; however, estimations based primarily on archeological evidence are also included.

13. As each premodern delta built gulfward in shallow marine waters, it was preceded by a blanket of marine to brackish marine prodelta clays

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* Dating by the Carbon-14 method has been described[107] as follows: "The basis of the method is magnificently simple. Carbon 14 is continuously produced in the upper atmosphere by the action of cosmic rays, which set free neutrons that transmute nitrogen in the air into the radioactive carbon. Incorporated in carbon dioxide, the radiocarbon moves through the atmosphere and is absorbed by plants. As long as they are alive, plants and animals go on ingesting radiocarbon. When an organism dies, and ceases to take in fresh carbon, its built-in clock begins to run down. The disintegrations of its carbon-14 atoms tick away the seconds and the years; in 5,568 years (on the average) only half of its original store of radiocarbon atoms is left, and in another 5,568 years only half of those, or one quarter of the original number.

"Long before that time, of course, most plants and animals have decayed into dust. But when the remains of an organism are fortuitously preserved, as a fossil or a house beam or a bit of charcoal, the age of the remains can be calculated. The amount of radiocarbon the organism possessed when it was alive is known; so is the rate of its radioactive disintegration. It is easy to compute the relic's age from the amount of radioactivity it still retains."

and silty clays. The intradelta complex of distributary front sands, interdistributary clays, and natural levee silts and silty clays advanced over the prodelta deposits. The premodern deltas are characterized by numerous deep, narrow distributaries and, in plan, the system of distributary-flanking natural levees resembles somewhat the radiating fingers of a spread hand. When the Mississippi changed its course and began construction of a new levee-ribbed deltaic lobe, the effects of subsidence became dominant within the abandoned delta. The gulfward periphery of the delta began a landward retreat forming, in many cases, arcuate sandy beaches consisting primarily of reworked distributary front deposits. Isles Dernieres and Grand Isle (see plate 1), which fringe the distal portion of the abandoned Lafourche delta, are examples of such beaches. The transgressive movement of the beaches, however, was not sufficiently rapid to keep pace with the forces of subsidence and, in time, large sounds and bays formed landward of the sandy arc. The Chandeleur Islands and Chandeleur Sound exemplify this late stage of delta deterioration. Although the distal regions of abandoned subsiding deltas were thus masked by marine sediments, the flanks, and in some cases more central portions, were concomitantly or subsequently overlapped by deposits of younger delta complexes.

14. The Balize Delta of the present Mississippi stands in marked contrast to the earlier delta complexes. Differences in shape, size, and distributary characteristics are obvious. Whereas the premodern deltas exhibited the typical roughly triangular outline, the adjective "bird's-foot" is often applied to the Balize Delta because of its plan configuration. The earlier deltas were much larger than Balize which has an area of only 300 sq miles. The St. Bernard Delta comprised an area of approximately 3000 sq miles; the Lafourche, 2500 sq miles; and the Teche, 2000 sq miles. The major distributary channels of the ancient deltas were more numerous than those of their modern counterpart and generally their lower branches had smaller angles of divergence between passes. In addition, ancient distributaries were deep and narrow, whereas the modern ones tend to be shallow and wide.

15. Differences are also found in the subsurface. In ancient delta deposits sands are restricted to thin, fairly widespread, distributary

front layers and to thick, narrow fillings of distributary channels. Sands, in the sedimentary framework of the modern delta, are found in wide, thick fingers which underlie the major distributaries. These dissimilarities between ancient and modern deltas can be explained by considering the depth of water into which each prograded. The modern Balize Delta has developed near the edge of the continental shelf in water originally reaching depths greater than 300 ft. In contrast, borings in the Lafourche and St. Bernard Delta complexes indicate that progradation occurred in waters ranging in depth from 30 to a gulfward maximum of 150 ft.

16. Thus, during the last 5000 years the shifting course of the Mississippi River had created the modern deltaic plain, a low-lying region of imperceptible slope and relief, consisting of marshland basins framed by interconnecting gulfward projecting natural levee ridges, and discontinuously fringed by sandy beaches. A region where the smooth arcuate shore line of the beach alternates with, or gulfwardly flanks, tortuously indented marshes. A land between earth and sea--belonging to neither and alternately claimed by both.

# PART III: PLEISTOCENE DEPOSITS AND THEIR PHYSICAL CHARACTERISTICS

17. Deltaic, deltaic-marine, and marine deposits are complexly interfingered in the deltaic plain of the Mississippi River. The key to interpreting the soil types found in borings made within the deltaic plain is the environments of deposition within which the soil was laid down or formed in situ. Nearly all the soils found in the subsurface or forming the surface were formed under conditions similar to those active in the delta region today. Studies of environments of deposition permit a reasonable approach to interpreting soil conditions between fairly widely spaced borings or in areas where no borings are available. Even where borings are very closely spaced, a blind correlation of soil types between adjacent borings may miss significant discontinuities in soil type readily apparent to those familiar with the environments of deposition in the deltaic plain. A commonly occurring case in point is the narrow wedge of sandy materials that often fills abandoned distributaries between fat clays of adjacent interdistributary areas. Borings spaced on 200-ft centers can easily miss these ribbons of coarser grained soils left behind as part of the deltaic plain as deltas advanced seaward or were abandoned.

18. Because an understanding of the depositional environments and their associated soil types depends on a knowledge of the geologic development of a region, the various sedimentary processes active in each environment are emphasized in the discussions which follow. The distribution of each environment, the soil types most commonly deposited in each, and various ranges of physical properties of predominant soil types are also discussed. Ancient deposits of Pleistocene age are treated as a unit, and described in this part. Recent deltaic plain deposits, overlying the Pleistocene, are subdivided into four major categories; the fluvial, the fluvial-marine, the paludal, and the marine environments of deposition, and are discussed in Part IV.

## Origin and Distribution

19. Pleistocene deposits are found at varying depths throughout most

of the study area. A fairly even surface of this ancient material lies at an average depth of 80 ft beneath New Orleans and rises northward to form a low, coastwise terrace north of Lake Pontchartrain (plates 2 and 3). During the last glacial advance (Late Wisconsin) this surface stood at heights of some 400 ft above sea level, the sea having been lowered as ice piled up on the continents. The material was subjected to tens of thousands of years of consolidation, dessication, oxidation, and erosion; it was warped downward to the south and uplifted to the north. As the ice retreated and sea level rose the surface was covered with a variable thickness of marine and fluvial deposits--Recent deposits which range from 0 to 17,000 years in age. Where the Pleistocene forms the present surface in the northern part of the study area it is called the Prairie Terrace, a sloping platform that stands at a level only slightly higher than that of the deltaic plain but consists, in contrast, of firm oxidized soils of considerable strength.

20. The southern margin of the Prairie Terrace is usually marked by a rather abrupt transition from the higher, undulating level to a flat, low-lying swamp level. However, in regions where natural levee sediments flank gently dipping terrace deposits the contact is not so apparent. For example, the "island" of Prairie south of Gonzales (30°10'N, 90°55'W) is partially masked by a thin cover of Mississippi River natural levee deposits.

21. Contours on the buried Pleistocene surface are shown in plate 4. Control for contours to depths of 100 ft below sea level is fairly good. Borings deep enough to encounter Pleistocene below this depth are relatively rare and the contours necessarily less accurate. Contours beyond this depth are based largely on studies conducted by Fisk and McFarlan.[27*] Considerable information is available in the Lac des Allemands and New Orleans areas, and larger scale maps (plates 4a and 4b) were prepared of these areas delineating the Pleistocene surface in considerably more detail than that shown in plate 4. As more data become available for more accurately contouring this eroded surface, the contours developed become

* Raised numbers refer to similarly numbered entries in the bibliography at the end of this report.

increasingly intricate. It is remarkable, however, that in some areas, where control is very good, reconstruction of this eroded surface shows it to be relatively undissected. For example, note the closely spaced borings on the sections crossing Lake Pontchartrain in plates 14 and 14a, and those in the section shown in plates 17-17b. The Pleistocene surface in these sections is remarkably regular, sloping only about 3 ft per mile.

## Recent-Pleistocene Contact

22. Determination of the contact between the Recent and Pleistocene deposits in borings is important from an engineering standpoint, and is usually a simple matter. The Recent deposits are typically dark gray or blue gray to fairly black. The upper portion of Pleistocene is characteristically oxidized to a yellow or buff color. On surface exposures care must be taken to distinguish the Pleistocene from natural levee deposits, which may also be oxidized to varying depths. Normally, the disposition or location of the deposit is sufficient to make this distinction. In other instances criteria other than color or disposition must be used. Where the Pleistocene lies beneath Recent deposits, a distinction on the basis of color is very diagnostic, particularly where the Pleistocene is at a depth of 50 ft or less below sea level. Here the color is typically a mottled tan or orange and greenish gray. At depths greater than 50 ft, the tan oxidized coloring is often absent and is replaced entirely by a greenish-gray cast not nearly so easy to distinguish from the overlying Recent. Other characteristics of Pleistocene deposits distinguishing them from overlying Recent materials are: (a) a marked decrease in water content, (b) a distinctive stiffening of soil consistency and a decrease in rate of penetration of sampling devices, (c) an increase in soil strength, and (d) the occurrence of calcareous concretions.

23. Care must be taken where the Pleistocene is at shallow depth to correctly interpret a tannish deposit, a few feet to 15 ft thick, which may overlie the Pleistocene. Water contents, consistencies, and strengths of this material are well within the range of the softer Recent materials. This oxidized material is interpreted as reworked or weathered Pleistocene deposits. The detailed subsurface section C-C' shown crossing Lake

Pontchartrain in plates 14-14a illustrates typical thicknesses and the erratic distribution of this material.

## Physical Characteristics

24. Section C-C', plates 14-14a, was developed from borings that penetrated from 100 to 130 ft of Pleistocene deposits, and portrays the variability of the soils. Since the Pleistocene was a former deltaic plain of the Mississippi River the variability of soil types should be expected--a variability comparable to that of the present deltaic plain--with environments of deposition and resulting lithologies very similar to those within the Recent.

25. Logs of borings made in Pleistocene deposits of the study area indicate that the predominant soil types found are clay and silty clay. Fig. 2 shows the percentage distribution of these and other soil types. Few available logs of borings utilized the Unified Soil Classification System;* rather, the older system illustrated in fig. 3 and based on sand-silt-clay content was utilized. Consequently, Atterberg limits available for the two predominant soil types have been plotted on a plasticity chart in fig. 2. Note that material classified as clay based on sand-silt-clay content falls principally within the CH range of the Unified System and that silty clay samples are about equally divided between CH and CL. As shown in fig. 2, cohesive strengths of the predominant soil types vary widely. Cohesive strengths of clays typically range between 900 and 2100 lb per sq ft and silty clays between 500 and 1300 lb per sq ft. However, several clay samples have cohesive strengths greater than 3000. Ranges in unit weight and in natural water content are also plotted in fig. 2.

26. Fig. 2 also shows a comparison of cohesive strength with depth. Two plots are included: one compares cohesive strength with depth of burial, the other with the depth of each sample below the Recent-Pleistocene contact. The latter plot was prepared because the effect of the recently deposited mantle of deltaic deposits over the older, much more consolidated

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* Waterways Experiment Station Technical Memorandum 3-357, The Unified Soil Classification System, March 1953.

Pleistocene might be relatively slight. The plots warrant the conclusion that cohesive strengths of similar lithologic units in the Pleistocene have little relation to depth of burial. Although there is a very slight trend indicating an increase in strength with depth of burial, the degree of scatter shown by the plot is far more striking. It is known that strength does not necessarily increase with depth in the upper crust of clays that have been subjected to oxidation and/or dessication. This so-called "drying crust" is a well-marked feature of Norwegian clay beds, the clay beds being characterized by a high shear strength and very often by a system of tiny fissures. The existence of a "drying crust" at the Recent-Pleistocene contact is suggested by the plot of samples below the Pleistocene surface. A slightly higher strength is indicated in the top 5 ft; however, the trend is not very pronounced, many of the uppermost Pleistocene materials falling within the lower strength ranges.

27. Strength of Pleistocene materials is almost uniformly good; however, as indicated in fig. 2, high variability in strength can be expected. The reasons for this are poorly understood. Occasionally, some of the finer grained strata within the Pleistocene are found to be oddly lacking in strength. Usually such occurrences are confined to the clays. Of interest in this connection are studies recently undertaken by Bjerrum[6] of the Norwegian Geotechnical Institute. In Norway, certain of the more active, fine-grained marine clays of glacial age have been found to be conspicuously lacking in strength. They are highly sensitive, often quick, i.e., exhibiting a complete loss of strength on remolding. The Norwegian clays were originally deposited in a marine environment but have subsequently been lifted above sea level. This has resulted in gradual drainage from the clays of saline waters and its replacement by fresh water. Loss of strength of the clays has been correlated by Norwegian investigators with this loss of salinity. A change in salt content, they have found, is accompanied by an appreciable change in plasticity and in such a way that the liquid limit and the plasticity index are lowered with decreasing salt concentration in the pore water.

28. A somewhat similar situation could exist within the Pleistocene clays that underlie the deltaic plain or rise as low terraces above it. The drop in sea level during the Ice Age (paragraph 7) allowed gradual

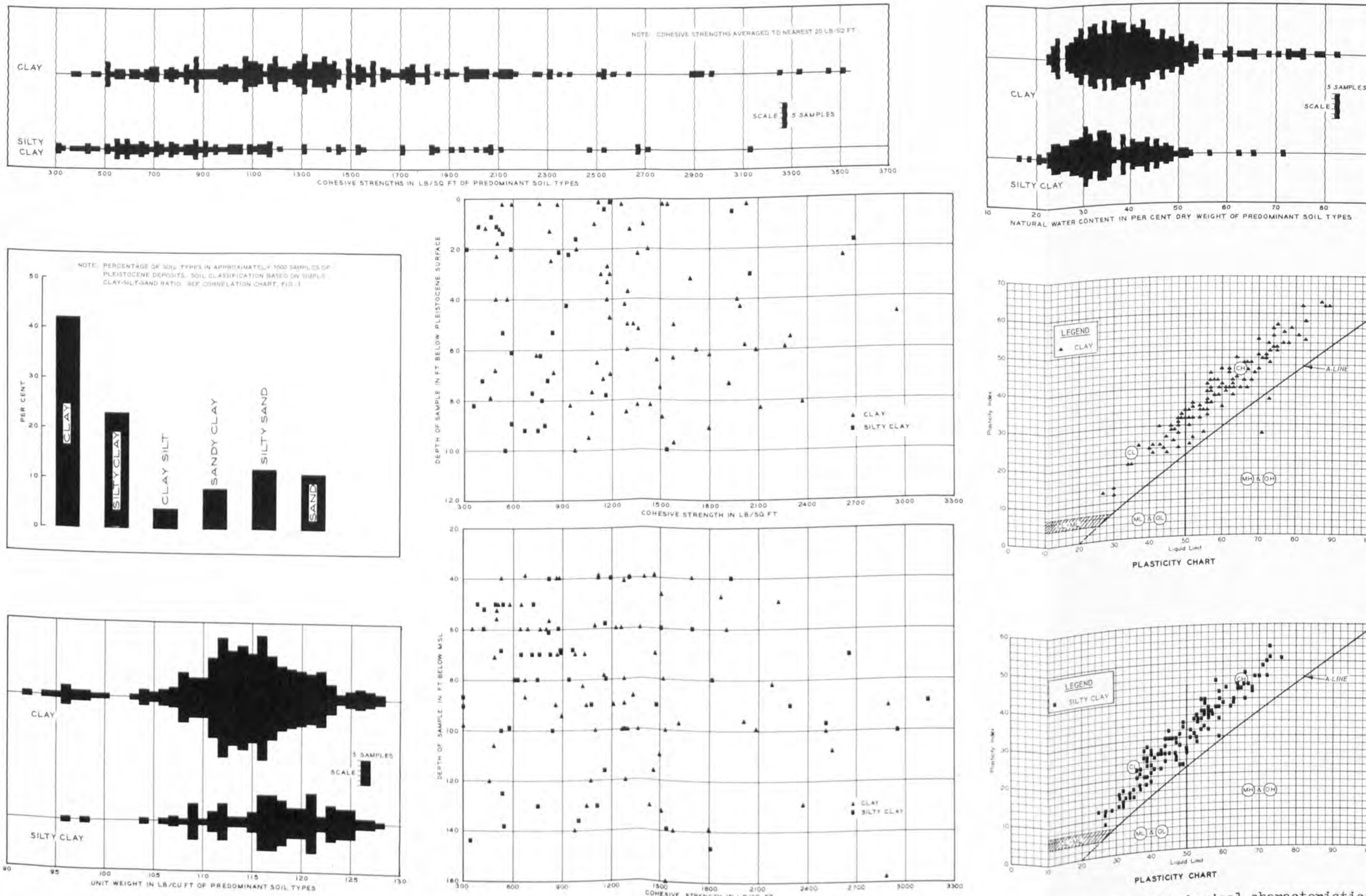



Fig. 2. Selected physical characteristics of Pleistocene soils

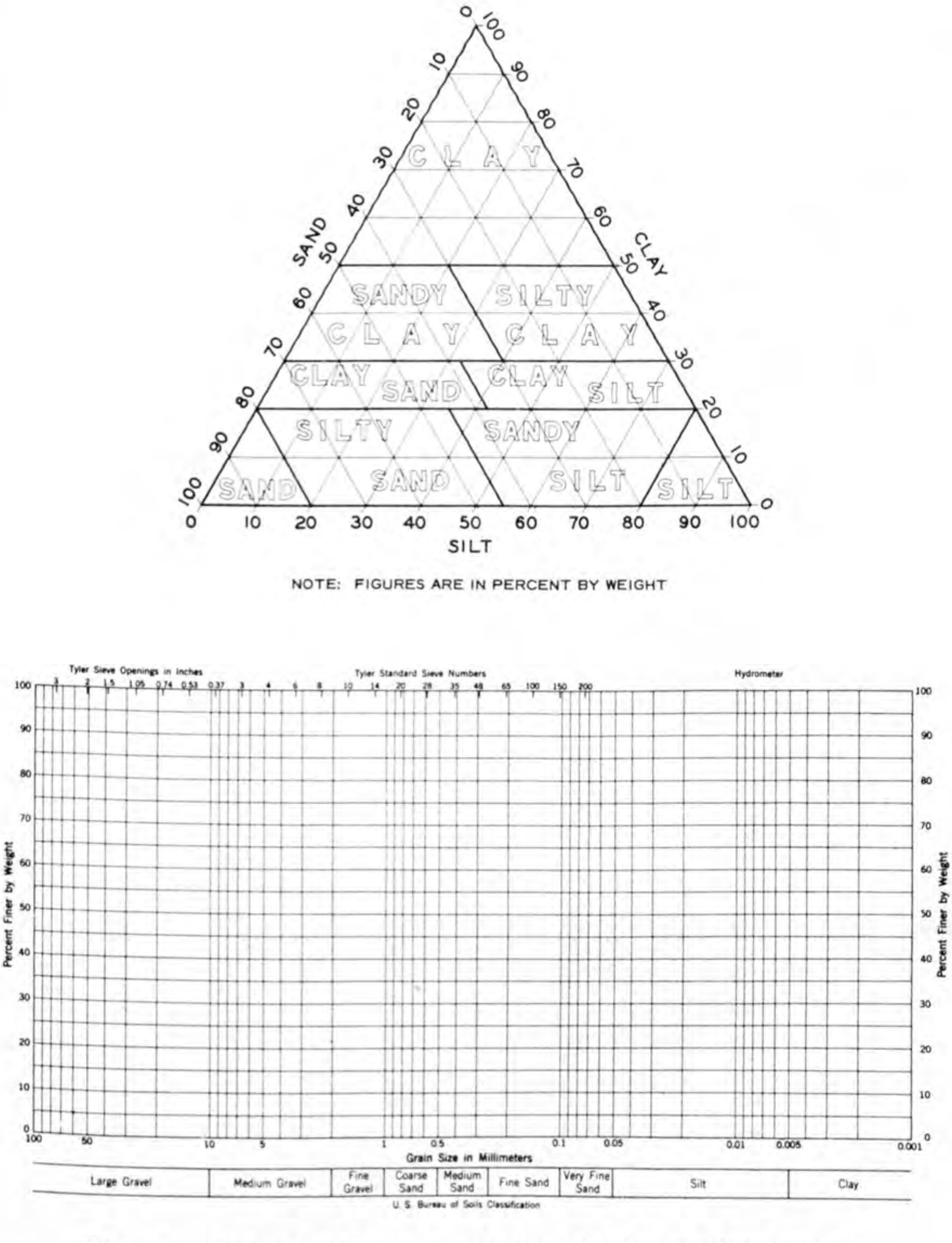



Fig. 3. Classification system used by Lower Mississippi Valley Division prior to 1950

drainage of saline waters from the Pleistocene clays. Subsequent rise in sea level may have only partially replaced the saline content of the Pleistocene and there is every reason to believe that conditions similar to those found within the Norwegian clays may occur locally. Consequently, although the occurrence of Pleistocene at shallow depth is normally considered fortunate from the standpoint of foundations within the deltaic plain, borings for larger structures should always penetrate the Pleistocene to sufficient depth to determine whether clays are present that have had their strength properties affected by loss of salinity. Tests should be made to determine the residual salinity of the soils and their remolding strength.

# PART IV: RECENT DEPOSITS AND THEIR PHYSICAL CHARACTERISTICS

29. The Recent deltaic plain deposits are the result of the outbuilding of the land surfaces seaward by the various past deltas and the present delta of the Mississippi River. Each time the Mississippi has extended its deltas seaward (see fig. 1), it has abandoned one overly extended course in favor of a shorter, more direct route to the sea. The chronology of the more recent delta shifts is described in Part II. The net result of these shifts in centers of deposition of the tremendous quantities of material carried to the gulf yearly by the Mississippi has been to distribute deltaic sediments in a 200-mile arc from the Chandeleur Islands area on the east to well beyond the limits of the study area on the west.

30. As soon as a delta of the Mississippi is abandoned, the sea begins to work its way inland. This process is aided by the subsidence of the whole of the deltaic plain, both tectonically and as a result of gradual consolidation of the soft, deltaic plain sediments. Yet the net result of the struggle between the advancing deltas on the one hand and the encroaching sea on the other is an over-all increase in size of the deltaic plain.

31. Four major environments are complexly interfingered in the formation of the deltaic plain: (a) fluvial sediments are deposited principally in the inland areas within and along streams and in fresh to brackish waters; (b) fluvial-marine deposits are laid down off the mouths of the deltas in brackish to marine waters; (c) organic deposits form in situ or are carried short distances and redeposited in the paludal environment; and (d) erosion and deposition by the sea result in those sediments associated solely with a marine environment.

## Fluvial Environments

32. Fluvial environments of deposition are restricted to (a) relatively narrow bands of sediment associated directly with active streams, the natural levees and the point bar deposits; and (b) those associated

with the final stages in stream history, the abandoned courses and abandoned distributaries.

Natural levees

33. Natural levees, the slightly elevated areas that flank alluvial streams, form the most conspicuous highs on the otherwise featureless deltaic plain. Nearly all the major inhabited and cultivated areas in the deltaic plain are located on them. Fig. 4 shows the general distribution of the major of these alluvial ridges.

34. Natural levees are formed by the deposition of the coarsest of the load carried in suspension by floodwaters that top the riverbanks. Widths and crest elevations of levees along active streams are functions of stage variation, volume, and load of the depositing stream. Along abandoned courses or distributaries the height of the natural levee reflects the amount of consolidation and subsidence that has taken place since deposition.

35. In the deltaic plain the natural levee flanking one side of the Mississippi may have a width of as much as 5 miles; 2- to 3-mile widths are most common. Widths of levees flanking active and abandoned distributaries vary from a few feet to more than a mile. Crest elevations of the natural levees along the present Mississippi decrease from 25 ft or more at Baton Rouge to mean sea level at Head of Passes or slope roughly at 0.1 ft per mile. The back slope of the levee varies with the size of the depositing stream. Large streams exhibit broad levees which gently slope toward the flanking marshes; levees along small streams are narrow with steep back slopes.

36. The thickness of natural levee deposits depends on the size of the depositing stream, their distance from the mouth of the stream, and the amount the levee has subsided into the underlying materials. Consolidation, in most cases, produces a downward bulge in the line of contact between the natural levee and the underlying deposits. This bulge occurs directly beneath the levee crests. Maximum thicknesses of the levee deposits range between 20 and 30 ft. Levee deposits at the extreme seaward ends of courses and distributaries may be less than 1 ft thick.

37. The types of materials forming the natural levees are functions of the size of the suspended load carried by the streams they flank. The

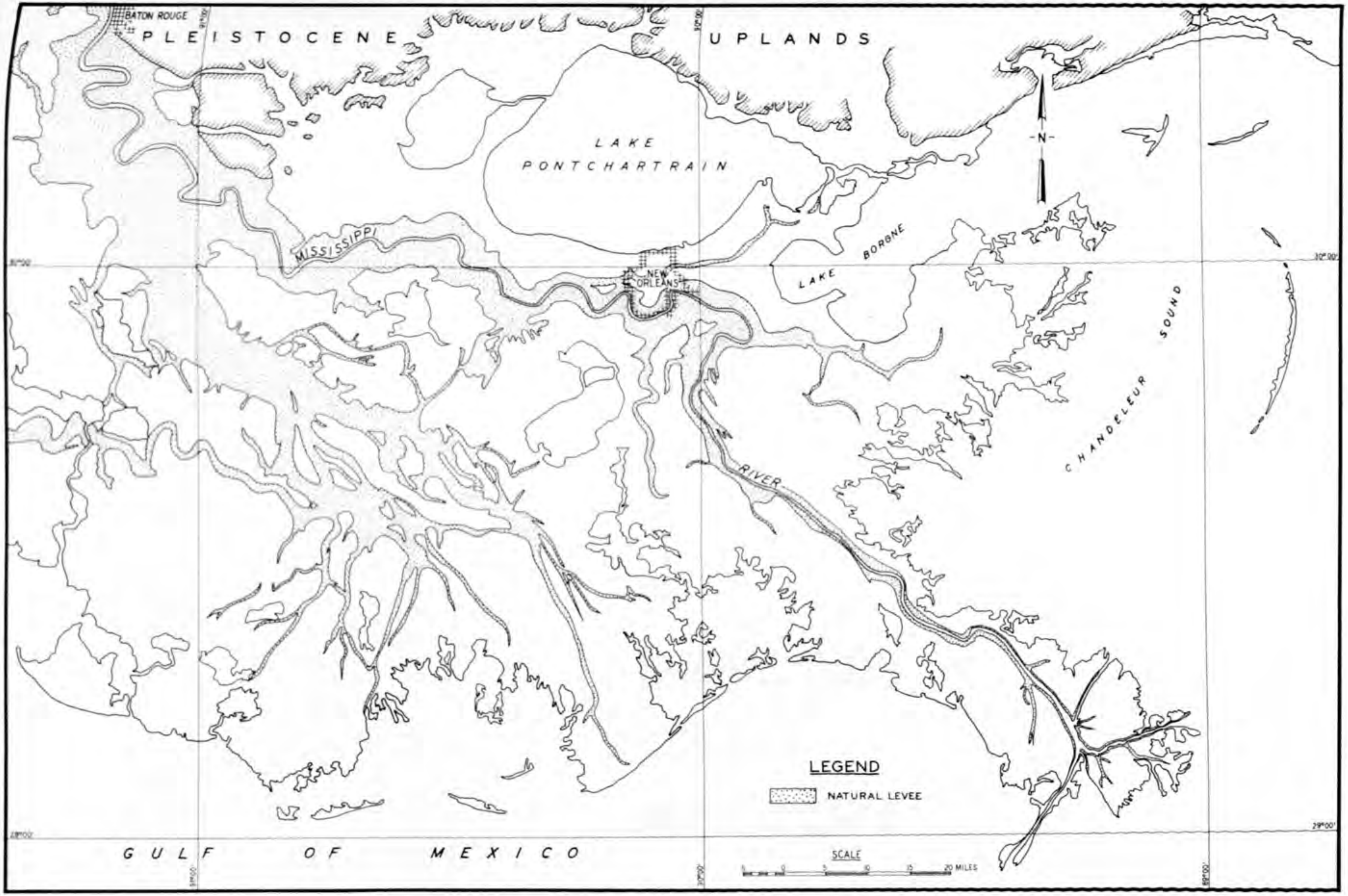



Fig. 4. Distribution of natural levee deposits

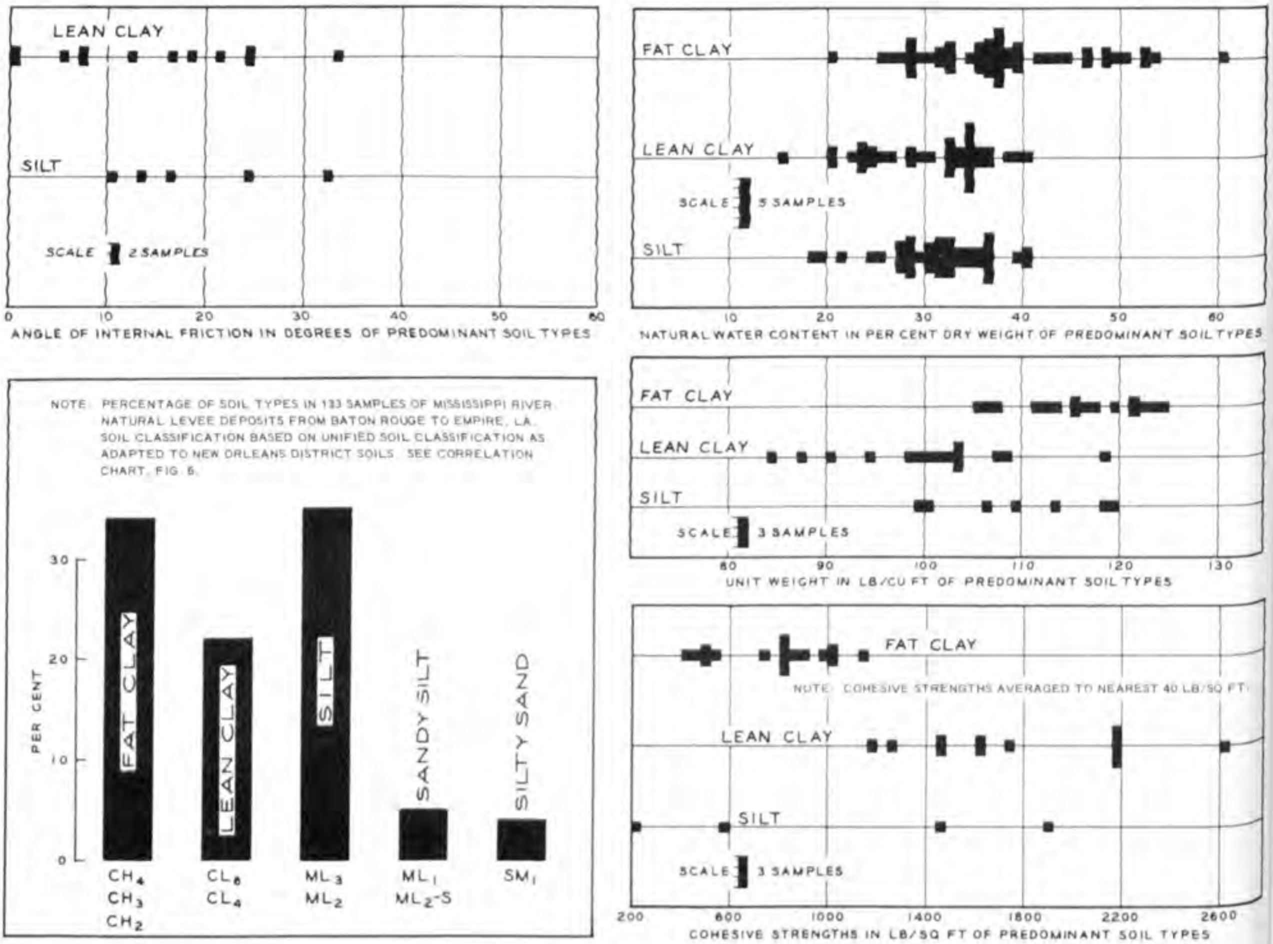



Fig. 5. Selected physical characteristics of natural levee soils

coarsest natural levee materials are those flanking present or abandoned courses of the Mississippi River. Fig. 5 summarizes data from several hundred borings penetrating the natural levee deposits that flank the Mississippi River from Baton Rouge to the gulf. Fat clay and silt account for two-thirds of the soil types found in these deposits. Lean clay makes up a considerable portion of the remaining third. Note the subdivisions of the standard soils units, e.g., $CH_4$, $CH_3$, $CH_2$. Fig. 6 shows the criteria on which these subdivisions are based. There is a distinctive decrease in grain size of the natural levee materials in a downstream direction. There is also a decrease in grain size from levee crest toward the flanking marshes. A third generalization is that in areas where there has been little or no stream migration or where stream migration has been toward the natural levee, grain size of the levee material decreases with depth below the crest. Where migration has been away from the levee there is a trend

| DEGREE OF PLASTICITY | | SOIL CLASSIFICATION | LETTER AND CORRELATION SUBSCRIPT | GRAIN-SIZE PERCENTAGES | | APPARENT PLASTICITY RANGE | | |
|---|---|---|---|---|---|---|---|---|
| | | | | SAND | CLAY | LIQUID LIMIT | PLASTICITY INDEX | |
| FINE – GRAINED SOILS | HIGH | FAT CLAY | $CH_4$ | 0-20 | 70-100 | 70-110 | 45-75 | |
| | | | $CH_3$ | 0-20 | 50-70 | 55-80 | 30-55 | |
| | | | $CH_2$ | 0-20 | 40-50 | 50-60 | 25-40 | |
| | | FAT CLAY (SANDY) | $CH_{3\text{-}S}$ | 20-50 | 50-70 | 50-70 | 25-50 | |
| | | | $CH_{2\text{-}S}$ | 20-30 | 40-50 | 50-60 | 25-40 | |
| | | | $CH_1$ | 30-60 | 40-50 | 50 | 30 | |
| | | FAT ORGANIC CLAY | ABOVE "A" LINE | BELOW "A" LINE | | ABOVE "A" LINE | | |
| | | | $CH_{OA}$ | $OH_A$ | 40-80 | 50 + | 22 + | |
| | | | $CH_{OB}$ | $OH_B$ | | 75 + | 40 + | |
| | | | $CH_{OC}$ | $OH_C$ | | 100 + | 60 + | |
| | LOW | LEAN CLAY | $CL_6$ | 0-20 | 30-40 | 40-50 | 20-35 | |
| | | | $CL_4$ | 0-20 | 20-30 | 28-43 | 10-25 | |
| | | SANDY CLAY | $CL_{6\text{-}S}$ | 20-30 | 30-40 | 40-50 | 20-35 | |
| | | | $CL_5$ | 30-60 | 30-40 | 30-45 | 15-30 | |
| | | | $CL_{4\text{-}S}$ | 20-38 | 20-30 | 25-40 | 8-20 | |
| | | | $CL_3$ | 38-60 | 20-30 | 20-35 | 3-15 | |
| | | LEAN ORGANIC CLAY | $CL_{OA}$ | | 10-40 | 30 + | 10 + | |
| | | | $CL_{OB}$ | | | 50 + | 25 + | |
| | | | $CL_{OC}$ | | | 70 + | 40 + | |
| | SLIGHT | SILT | $ML_3$ | 0-20 | 5-15 | 25-28 | 2-6 | |
| | | | $ML_2$ | 0-20 | 5-20 | 22-28 | 0-6 | |
| | | SANDY SILT | $ML_{2\text{-}S}$ | 20-45 | 5-20 | 17-28 | 0-6 | |
| | | | $ML_1$ | 45-60 | 0-15 | 15-20 | 0-6 | |
| | | ORGANIC SILT | $OL_4$ | 0-20 | 20-30 | 30-40 | 6-15 | |
| | | | $OL_2$ | 0-20 | 5-20 | 28-40 | 2-10 | |
| | | ORGANIC SANDY SILT | $OL_{2\text{-}S}$ | 20-45 | 5-20 | 28-35 | 0-6 | |
| | | | $OL_1$ | 45-60 | 0-15 | 30 | 0-5 | |
| SAND & SANDY SOILS – NONE TO SLIGHT PLASTICITY | | CLAYEY SAND | $SC_{5\text{-}S}$ | 60-70 | 30-40 | >28 | >6 | MINUS 35 MESH |
| | | | $SC_{3\text{-}S}$ | 60-80 | 20-30 | | | |
| | | | $SC_1$ | 60-90 | 10-20 | | | |
| | | SILTY SAND | $SM_1$ | 60-80 | 0-15 | <28 | <6 | |
| | | SAND | $SM_{1\text{-}S}$ | 80-90 | 0-20 | NONPLASTIC | | |
| | | | SP | 90-100 | 0-10 | | | |
| FIBROUS ORGANIC SOILS | | PEAT | PT | | | 200 + | | |

Fig. 6. Unified Soil Classification adapted to New Orleans District soils May 1949

toward increase in grain size with depth.

38. Cohesive strengths of natural levee materials are high when compared with most deltaic plain deposits. As shown in fig. 5 the cohesive strengths of the clays range most typically between 800 and 1200 lb per sq ft.

39. No comparable data have been analyzed to determine the strength and soil types in the natural levees developed along the many minor streams in the deltaic plain. Generally speaking, a predominance of fat and lean clays of fairly high strength should be expected.

40. The positions of many of the natural levees in the deltaic plain are readily apparent on topographic maps or aerial photographs. Where they have subsided beneath the marsh, however, recognition is often difficult. Faint vegetative or linear trends are often the only surface traces which can be used to identify such buried features. Borings encountering these deposits usually find material distinctively stiffer than overlying deposits and quite often oxidized to a tan or reddish color. Oxidation, however, is not an entirely reliable criterion for recognition of natural levee deposits. Treadwell[103] cites a situation just east of Lake Machias (29°45'N, 89°30'W) where an Indian midden rests on unoxidized natural levee. This indicates, he suggests, either that the levees were built no more than a few inches above water level and oxidation could not begin, or that large levees were formed, oxidized, and later chemically reduced upon burial due to subsidence. The fact that a large Indian habitation was located on the levee at this locality suggests that the levee stood far more than a few inches above water level. The conclusion is inescapable that oxidized levees may become chemically reduced on being buried beneath marsh.

<u>Point bar</u>

41. Point bar deposits are formed by lateral migration of the river or its distributaries. Point bar deposition along distributaries is relatively insignificant within the delta region. As shown in fig. 7, the deposits become more and more extensive in an upstream direction along the present Mississippi River. Somewhat less extensive, but nevertheless well developed, are zones of point bar deposition along abandoned courses of the Mississippi such as those found along Bayous La Loutre, Teche, Barataria, and Lafourche.

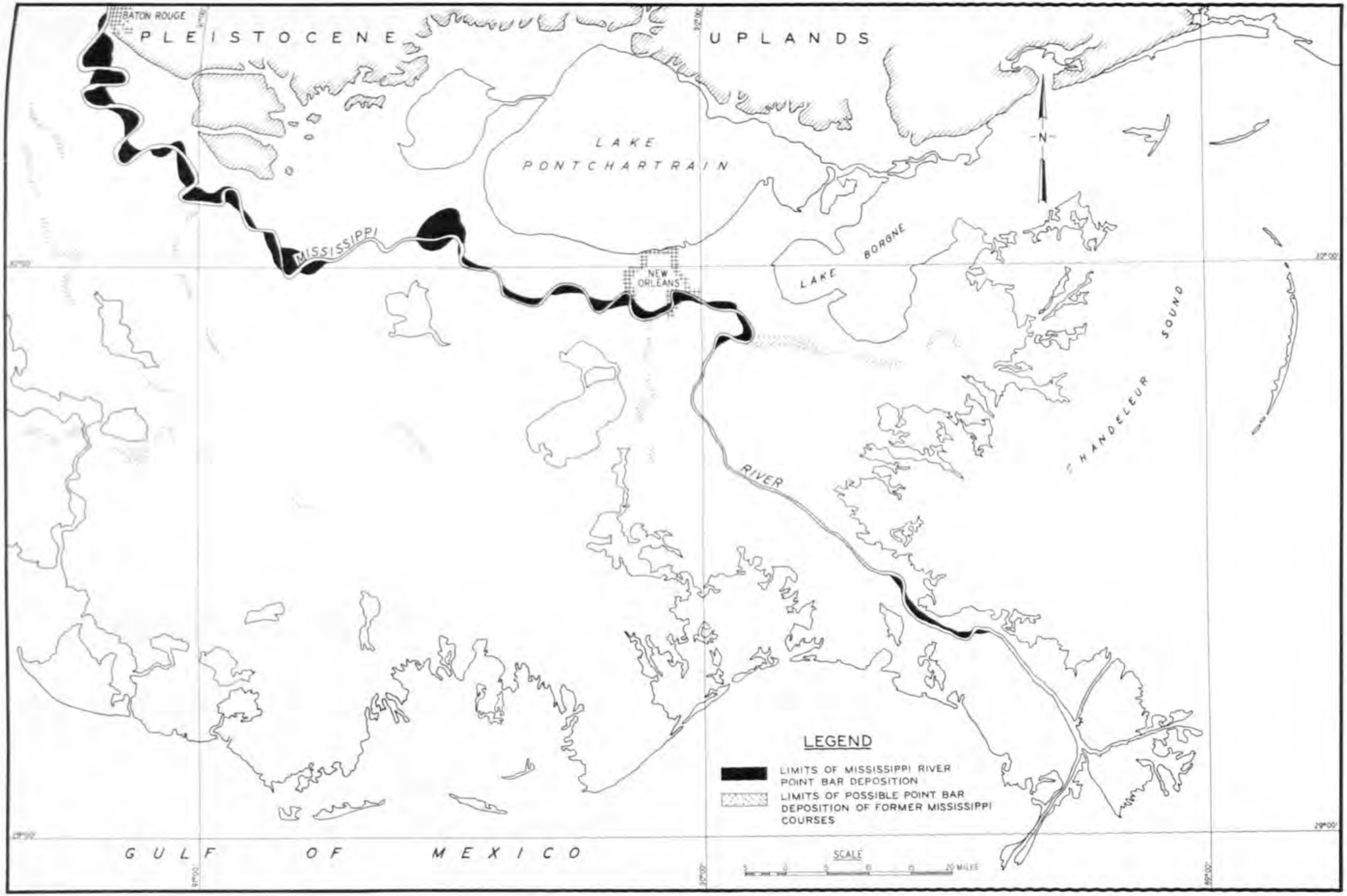



Fig. 7. Distribution of point bar deposits

42. Meandering of the Mississippi River in the alluvial valley upstream from the delta study area has been much more active than within this lowermost portion of the plain. Whereas the river in the upper alluvial valley has been known to migrate in some reaches more than 500 ft per year, the rate of migration in the study area, even in major bends such as Missouri Bend just downstream from Baton Rouge, is in the order of only 25 ft per year. There are two reasons for this slow rate of migration: first, the river within the southern portions of the valley is forced in many instances to migrate into tight, clayey Recent materials or stiff Pleistocene clays which effectively resist erosion, and second, corollary to the first, the river does not begin any noticeable meandering habit until it begins to scour into coarse materials. Much fine and very fine sand is carried by the stream as suspended or bed load to the mouth where it forms a part of the coarser portion of the delta complex. Where the stream encounters medium or coarse-grained sand, on the other hand, or considerable concentrations of fine-grained sand, much of this material is deposited a short distance downstream. Opposite the areas of deposition the river begins to scour. More coarse material is carried to the opposite bar, and in this way meanders in this lower portion of the river appear to be initiated.

43. An example of such a process is the area of point bar deposition and the two bends forming at and just south of Sixty Mile Point (29°35'N, 89°35'W). Here the river is scouring into what may be a series of buried beach ridges (see fig. 25), picking up the beach sands and shell detritus and depositing them downstream within the two bend areas.

44. Point bar deposits in the upper portions of the valley are characterized by a series of alternating swales and ridges. The former are the sites of fairly deep clay deposits, the latter are areas of silty sand or sandy silt underlain at very moderate depths (10 to 25 ft) by clean sands. In the deltaic plain, swales, as such, are relatively rare. In order for swales to be formed, a situation must exist within a point bar area wherein rapid deposition on a bend during high river stages leaves an arcuate low between one period of deposition and the next. During subsequent high stages, one or several such lows within a point bar area are chosen as routes for floodwater drainage, scoured to some depth, and finally filled with clayey sediments from subsequent overbank flow. In

the study area rates of point bar accretion are so slow that no perceptible lows are formed, and the process so common along the river upstream is not generally duplicated.

45. Instead, point bar deposits consist of varying thicknesses of a fine-grained topstratum, underlain at variable depths by relatively clean, river channel sands. The thickness of this topstratum within the study area ranges from 25 to 75 ft, the thicker topstratum occurring in a downstream direction. Substratum sands--often intercalated with lenses of finer materials--reach depths roughly comparable to present river scour. Fig. 8 shows the percentage of soil types in a series of borings made in point bar deposits along the Mississippi River from Baton Rouge to New

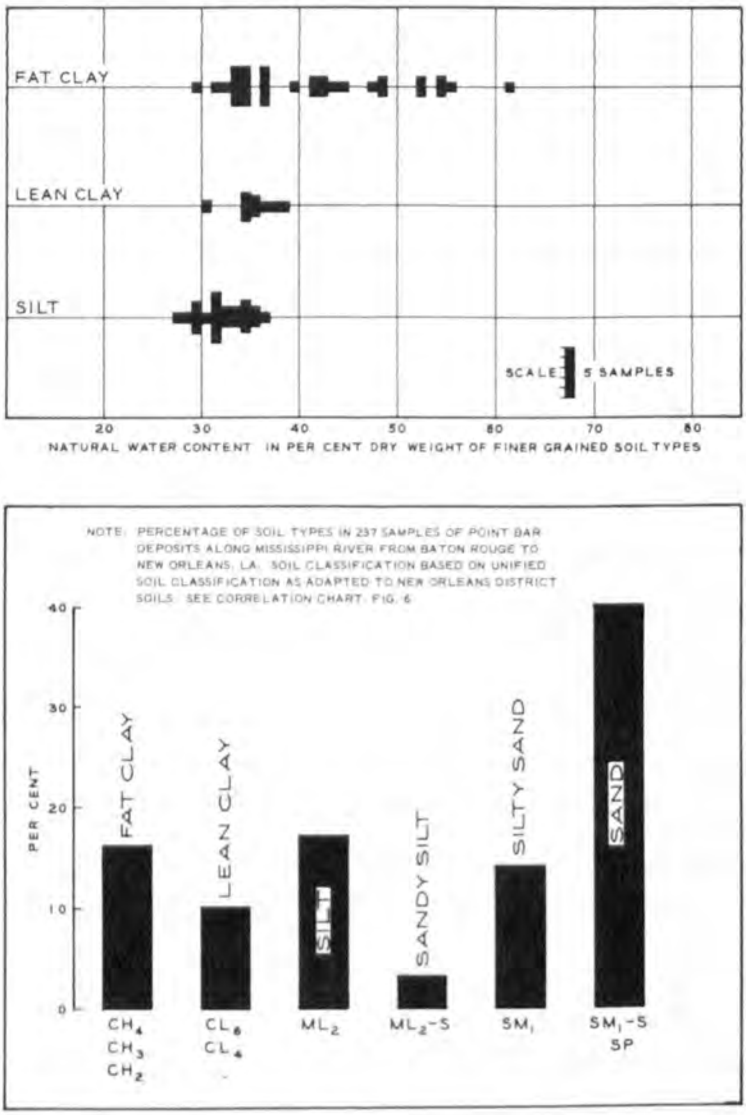



Fig. 8. Selected physical characteristics of point bar soils

Orleans. The high percentage of sand is a reflection of the sandy substratum portion of the point bar materials. Strengths of point bar deposits are normally high. Organic content is low.

46. Point bar deposits are associated almost entirely with the major courses. Few distributaries in the deltaic plain have meandered sufficiently to allow their development. In borings the sandy nature of the point bar, particularly of the point bar substratum, aids in its recognition. It is distinguished from buried sand beaches by its position in relation to the present and abandoned river courses and by the fact that beach sands are often mixed with shell fragments. Point bar deposits contain shell fragments only rarely.

Abandoned courses

47. Abandoned course deposits fill the main channel left by the river when it is diverted at some point upstream into a new and shorter course to the sea. Five and possibly six major course diversions have occurred within the study area (fig. 1). In each instance the river was diverted a considerable distance upstream from its mouth, leaving behind a channel capable of carrying nearly the full flow of the Mississippi. Studies[107] of the possible diversion of the Mississippi through its Atchafalaya distributary north of Baton Rouge have indicated the most probable method of abandonment and filling in of these abandoned courses and the types of deposits that can be expected within them.

48. Indications are that the abandonment of a Mississippi River course is a gradual process until a critical stage in the diversion process is reached. This critical stage usually occurs when 30 to 50 per cent of the master stream's flow is being diverted through the diversion arm. Following this critical stage there appears to be a rapid acceleration of the diversion process during which the former full-flow course is plugged with sand just downstream from the point of diversion and the new channel rapidly enlarges to take the entire flow. After abandonment of the former course, only high water or flood flow is capable of breaching the sandy wedge which forms at the head of the abandoned course. Sandy materials are distributed for some distance downstream from this point by these flows, but most of the abandoned course receives only the finest materials which are carried in suspension.

49. For most of its length and for a considerable time after abandonment, the course is a fairly deep elongate water body which gradually fills with fine-grained sediments carried in by flood flow in much the same way that the shorter segments of the stream isolated as chute or neck cutoffs are filled. If this were the only source of material the resulting body of sediment would consist of a wedge of sand, gradually thinning downstream, overlain by a complementary clay wedge thinning upstream. However, indications are that in the deltaic plain this sequence is complicated by the introduction of both clays and sandy materials carried upstream and deposited in the abandoned course by tidal currents.

50. Data are too sparse at present to determine the effects of these currents on the seaward portions of the filling course, but available boring data on the abandoned St. Bernard Course indicate that a sandy wedge may develop upstream from the seaward extremities of the abandoned course in much the same way as one develops downstream from the course's landward extremity or its point of diversion from the main stream. A hypothetical reconstruction of the filling process would involve consideration of the shoal that would have been in existence at the St. Bernard Course "Head of Passes (29°50'N, 89°25'W)," where a series of branching distributaries once divided the flow from the course and transported it seaward through several smaller and shallower channels (see plate 5). On being abandoned, the course channel would have been considerably deeper upstream from this shoal and tidal currents would have been able to carry sediment into this deeper pool building a sandy wedge upstream in the same manner that fluvial currents were building a sandy wedge downstream from the point of diversion. The central portions of the abandoned course under this hypothesis would be the site of maximum clay and silt deposition.

51. Even though present knowledge of the sediments filling abandoned courses is meager, there is every indication that the ribbons of abandoned course deposits in the deltaic plain afford some of the firmest foundation materials at comparatively shallow depth in the region. There is always an upper zone of low-strength material with high water content, fairly high organic content, and low bearing capacity that may range from 20 to 100 ft in thickness depending on the distance of the deposit from the original point of diversion. However, below this upper zone, high strength sand and

silty sand are the most common soil types and these may reach thicknesses of from 30 to 100 ft. Organic content in this lower zone is negligible.

Abandoned distributaries

52. The abandonment of distributaries is an integral part of delta advance and hundreds, or perhaps thousands, of narrow bands of distinctive sediments filling abandoned distributaries emphasize the importance of this environment in the deltaic plain. Abandoned distributaries range from a few feet to more than 1000 ft in width, and deposits filling them range from a few feet of organic material--more logically considered part of the flanking marsh deposits--to wedges of distinctive inorganic sediments 50 ft or more deep. Plate 5 shows the positions of the major abandoned distributaries as well as their larger, deeper counterparts, the abandoned courses. Data on this plate were taken from references 22, 103, 111, and 119 and modified by airphoto interpretation and boring information. Only the larger, more obvious abandoned distributaries that have left distinctive bands of sediment as part of the deltaic plain are shown in plate 5.

53. The processes involved in distributary development have been explored by several investigators. Welder[119] made an extensive study of the development of the Cubit's Gap system of distributaries in the present delta; these distributaries were formed by the crevassing--in this instance the artificially induced crevassing--of the low natural levee near Head of Passes. He and others[25, 107, 111] have considered the typical development of distributaries as load is deposited at the mouths of individual channels where they enter the sea. A shoal sandy bar is formed, around which the channel bifurcates. Each channel then continues its own development, and splits in turn to form new distributaries. The result is a network of channels which distribute the water of the main channel through a series of minor channels to the sea. The intricacy of this network ranges from many distributaries, the so-called "horsetail" delta left by the Lafourche-Mississippi course, through less intricate systems such as those formed by the St. Bernard, to the "bird's-foot"[88] type of delta distributary system with only a few operative distributaries presently forming at Head of Passes. Indications are that the intricacy of the distributary pattern can be correlated with the depth of water in which the distributary system advances. Where the water body into which the delta was built

is shallow, many deep narrow distributaries are typical. Where the original depth of water is deep and the distributaries must form entirely within the coarser materials forming the bars at their mouths, fewer, wider, distributaries are developed.

54. The process of abandonment of a distributary is believed to parallel closely that of the abandonment of a course. Wedges of sand are built at the point where the distributary leaves the main course. These extend for variable distances downstream. In the sizeable Metairie distributary of the Mississippi that trends through New Orleans (fig. 9) the few borings available indicate a sand wedge filling the bottom of the abandoned distributary that extends downstream for a distance of about 9 miles. Overlying this sand wedge is a complementary wedge of fine-grained material. It is doubtful if a sand wedge of such size is developed in any but the largest of distributaries. However, deep, narrow, sand-filled distributaries are known to exist in the abandoned Lafourche Delta. Welder[119] tested materials filling Robinson Pass (29°15'N, 89°10'W), one of the minor abandoned distributaries in the deltaic complex south of Main Pass at Head of Passes. He found a clay fill underlain by a distinctive wedge of silty clay and clay silt. Again, borings that have penetrated a considerable section of organic clays and peats have been interpreted as representative of abandoned distributary fill. Present indications are that materials forming the distributary fill are highly variable but a wedge of relatively coarse material, compared to the remainder of the distributary fill, always plugs the upstream end.

## Fluvial-marine Environments

55. The sequence of fluvial-marine deposition results in a complexly interstratified deposit which, nevertheless, can be divided into distinctive lithologic entities. Preceding each deltaic advance into a water body is a wave of fine-grained deposition swept seaward by the stream and redistributed by longshore and tidal currents. These are the prodelta deposits--clays at some distance from the mouths of the deltas and silty clays near the delta front. As the delta advances, each distributary is built seaward on a bed of the coarsest material carried by the stream--in

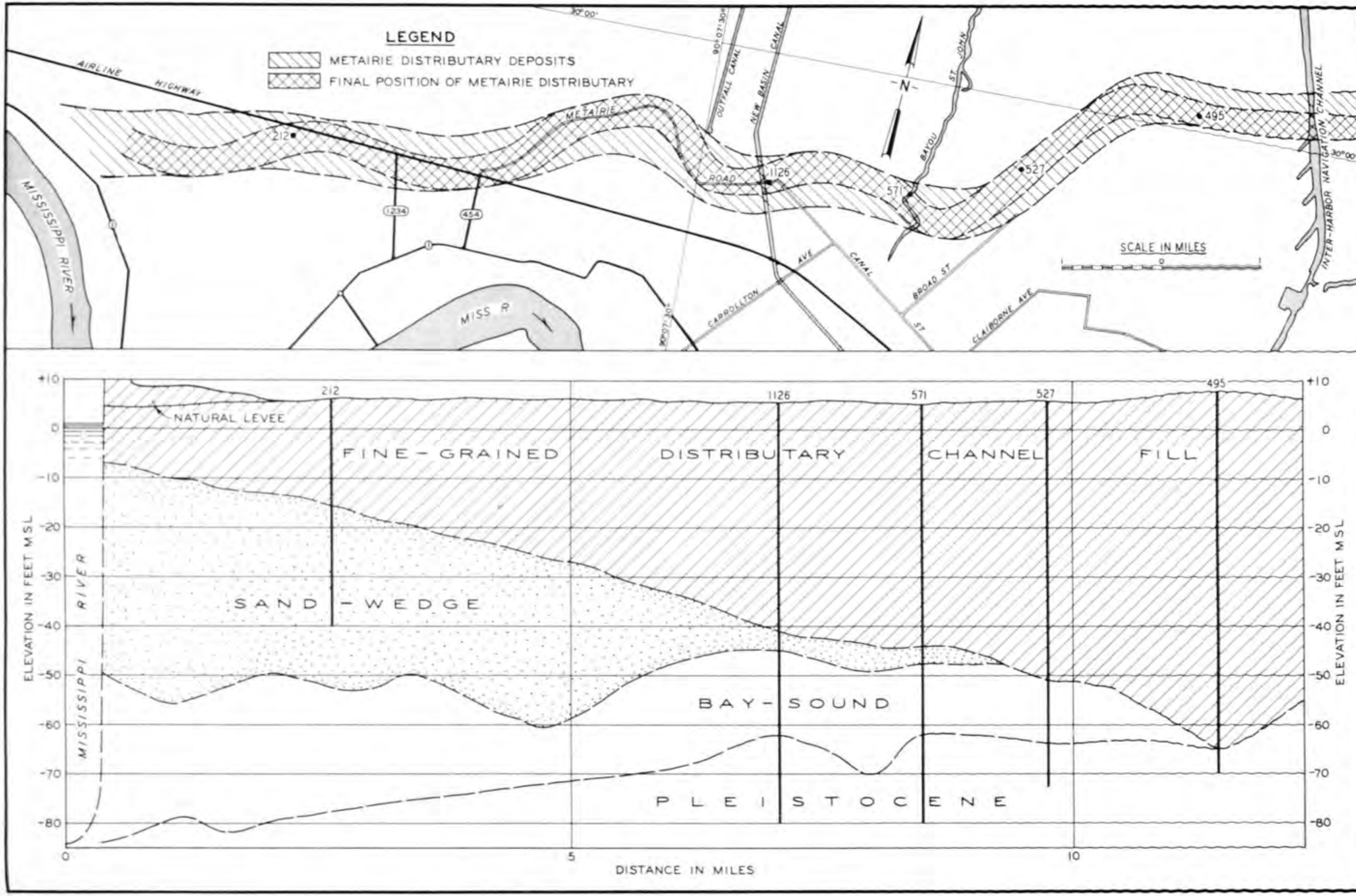



Fig. 9. Sand wedge developed in Metairie distributary

the case of the Mississippi, fine-grained sand. The coarser sediment settles near the mouths of the distributaries as subaqueous bars, and along their margins first as subaqueous, then above-water natural levees. Land surfaces form as the sediments build up to and above the level of the sea. This is the intradelta environment. As distributaries continue to extend themselves seaward, well-defined lowlands develop between them. Into these areas only the fine-grained deposits are carried by distributary overflow, wind, or tidal currents. So that within, or more normally overlying the intradelta coarser materials are discrete, wedge-shaped bodies of interdistributary clays.

56. The three fluvial-marine environments of deposition, the prodelta, and interdistributary, and the intradelta, make up an estimated 75 per cent of the Recent deposits of the deltaic plain. In effect, all the sediment carried to the sea as suspended and bed load by the Mississippi River is deposited in one of these environments. Estimates of the amount of sediment carried to the gulf by the Mississippi vary but 400 to 500 million tons annually is generally accepted as the right order of magnitude.

## Prodelta

57. Thickness and distribution. Prodelta deposits are the first terrigenous sediments introduced into a depositional area by an advancing delta. Although widely distributed by wind, marine, and fluvial currents, there is a gradation of prodelta silty clays into prodelta clays with distance from the mouths of active distributaries. This situation is well illustrated off the mouth of the present Mississippi Delta where silty clays merge seaward with clays (see plate 2). In profile this depositional sequence is manifested by a normal gradation upward in the prodelta clay sequence from fine to coarse, in this instance from the finest clays to silty, and rarely, sandy clays.

58. Prodelta deposits are some of the most homogeneous and widespread of the environments of stream deposition. A wave of this type of sedimentation preceded the seaward advance of each of the deltas making up the deltaic plain, and the result has been a build-up of considerable thicknesses of the prodelta deposit. Detailed control provided by relatively closely spaced borings shown on section E-E', plates 17-17b,

illustrates the homogeneity and gradual seaward thickening of this deposit. Limited control in the Head of Passes area and off the coast of southeastern Louisiana from New Orleans southward to the gulf indicates great thicknesses of prodelta clays.[27, 28, 64] Prodelta deposits overlie substratum sands and gravels in the western portion of the study area and nearshore gulf deposits in the eastern portion of the study area. They may directly overlie the Pleistocene where nearshore gulf deposits, or their landward equivalent, the bay-shore sequence, have not developed. More rarely, in areas where a deltaic sequence has been abandoned and has subsided beneath the marsh, or where distributaries of consequence have developed considerable distances upstream from the main delta area, prodelta clays may overlie these active delta sequences. Detailed borings are necessary to isolate such areally insignificant prodelta deposits however, and it is usually more practicable to include them within the complexly interfingered deposits that form immediately adjacent to or within the subaerial deltaic mass as it advances, the intradelta and interdistributary sequences. Only significant thicknesses of prodelta deposits are delineated in the subsurface sections shown in plates 10-17.

59. The distribution and subsurface limits of the prodelta deposits have been explored fairly well in the eastern, particularly the northeastern, portion of the study area. Their thickness has also been tested at Head of Passes. Farther to the west less is known of their thickness and general distribution. Each advance of the essentially overlapping deltas of the Teche, the Lafourche, and older deltas, was preceded by a wave of prodelta clay deposition. A few scattered borings made for engineering structures in the offshore areas of southern Louisiana indicate a thickness of these deposits ranging between 400 and 500 ft.[28, 64] In some of these deep offshore borings thin fine sand or silty sand lenses, on the order of 10 to 20 ft thick, are found in the otherwise homogeneous clay sequence. When more data are available it may be possible to correlate these sandy lenses with the advance of each of the major deltaic systems. This correlation is suggested by the fact that the coarser lenses appear to become less abundant with distance offshore or with distance from an abandoned delta so that at a variable distance from shore borings indicate an uninterrupted vertical sequence of prodelta clays.

60. In summary, prodelta clays are distributed in plan as a relatively uninterrupted stratum beneath the shallow waters of offshore southeastern Louisiana. Lenses of this environment extend inland beneath the land areas but greatest thicknesses occur in the offshore areas. The thickness varies generally with the depth to Pleistocene; the greater the depth to this ancient sedimentary horizon, the greater the thickness of prodelta clay.

61. Physical properties. Fig. 10 shows the predominant soil types associated with the prodelta environment and some of their physical characteristics. As can be seen from the bar graph of the soil types, about 96 per cent of the deposit consists of fat clay (CH). A further subdivision based on an adaption of the Unified Soil Classification to fine-grained soils (fig. 6) indicates that the prodelta consists predominantly (78 per cent) of the finest of the fat clays, the $CH_4$ classification, containing from 70 to 100 per cent clay sizes.

62. Natural water contents of the predominant fat clays range from 30 to 90 per cent dry weight; and their unit weight ranges from 92 to 118 lb per cu ft. Cohesive strengths of the prodelta clays are relatively high. As shown by fig. 10, the characteristic range in strength is between 200 and 700 lb per sq ft. Cohesive strengths greater than 1000 lb per sq ft are not uncommon at depth. That there is a definite increase of strength with depth is shown in the plot in fig. 10. However, the scatter in the plot of water contents of the clays with depth suggests that the increase in strength is due only partially to consolidation under load. It should be pointed out that samples used in preparing fig. 10 were all from the well-defined prodelta sequence in the St. Bernard Delta or the northeastern part of the study area.

63. Fisk[28] and McClelland[64] present interesting data based on widely scattered borings of the much thicker prodelta clay sequence off southern coastal Louisiana. McClelland selects three borings, one in an area of active deposition off North Pass (at the mouth of Pass a Loutre); one in the offshore area west of the present delta and about 15 miles southwest of Venice, Louisiana; and one about 3 miles off the mouth of Bayou Lafourche. Each of these borings penetrates about 200 ft of a fairly uninterrupted sequence of clay. In the first boring, in the area of active deposition,

the top 60 ft of clay has a uniformly low strength. Below this layer strength increases progressively with depth. The upper 60 ft are interdistributary clays, deposited relatively rapidly as the delta extended itself seaward. There has been insufficient time for the upper clays to consolidate and the lower prodelta clays, formerly normally consolidated, are being further consolidated under the newly acquired load. The second boring is located in an area of relatively uninterrupted prodelta clay deposition; first as an offshore area of the abandoned Lafourche Delta and subsequently as an offshore area of the most recent extensions of the delta system southward from New Orleans. The clays are normally consolidated, showing an almost straight-line increase of strength with depth from zero strength at the mudline to about 1200 lb per sq ft at 200 ft. The third boring off Bayou Lafourche is located in about 28 ft of water in an area which was once a land surface of the Lafourche Delta but which has subsided and is now being subjected to marine erosion. Here moderate soil strengths of the order of 220 lb per sq ft are found at the mudline and increase to about 1200 lb per sq ft at 200 ft. These are considered to be overconsolidated clays in an area where overlying strata have been removed.

64. Mudflats and mudlumps. Two phenomena in the deltaic plain directly associated with prodelta deposition are the mudflats and the mudlumps. Extensive mudflats of the type now forming along the Iberia-Cameron Parish shore line of south central and southwestern Louisiana are not found in the study area.[71] However, such deposits should be present in the subsurface. Mudflats occur where the influx of fluvially introduced clays is predominant over beach-forming processes along a shore line. As the sediment accumulates and builds upward to within a foot or so of the average water level, marsh plants become established along the inner margins of the flats. The vegetation tends to trap more sediment and eventually the grass-covered flats are exposed even at low tide. If the influx and deposition of sediment are not curtailed, the accretionary processes continue and the former shore line is stranded behind a growing mudflat crowned with a similarly gulfward-advancing zone of marsh. A beach deposit so stranded is known as a chenier.

65. The shape and thickness of the mudflat prism of sediments are, of course, dependent on the original bottom configuration. Similarly,

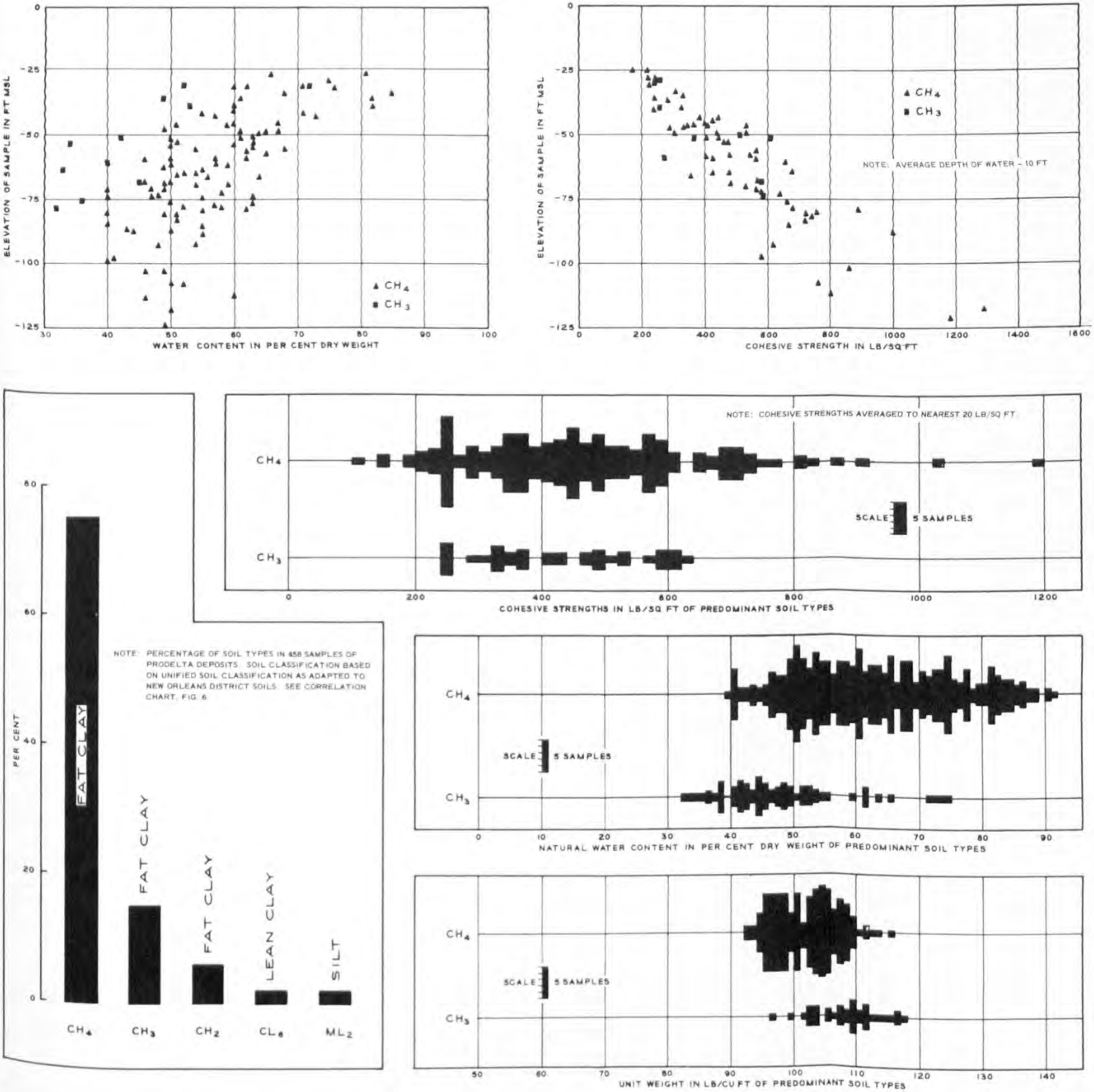



Fig. 10. Selected physical characteristics of prodelta soils

dependent on the composition of the original bottom, the sediments may overlie marsh clays or sand-silt gulf-bottom deposits. In time subsidence allows the marsh to overtop the entire association of deposits and temporary cessation of clayey sedimentation may once again permit beach formation. Such a process has resulted, particularly in southwest Louisiana, in groups of beaches stranded at varying intervals inland from the present shore line, between many of which are mudflat deposits buried beneath marsh deposits.

66. Mudflat deposits consist predominantly of watery clays and silts. However, the percentage of sediment coarser than 0.01 mm usually ranges from 20 to 25 per cent. In some places the mudflats consist of very uniform, fine-grained clay, while in others there are thin silt partings, the result of wave-winnowing, in the mud deposit. Water content in mudflat deposits is consistently high. Organic particles may be disseminated throughout portions of the deposit if large swash-line accumulations of reworked plant material are present during the formation of the mudflat. This situation is most common along bay shores. Compared with the usual prodelta clays, mudflat clays are notably higher in organic content. When first deposited, the watery mudflats have almost no bearing capacity. A man rapidly sinks to hip-depth in these deposits of clayey ooze provided the original bottom is not encountered. Through concentration of coarser sediments by wave-winnowing, and stabilization through marsh grass growth, the deposits may eventually develop engineering properties similar to normal prodelta clays.

67. Mudflat deposits undoubtedly form portions of the top 20 ft of the deltaic plain. Where mudflats occur, they should cover relatively wide expanses, and should consist of shallow, homogeneous clays with a fairly high percentage of detrital organic matter. They are distinguishable from the marsh deposits, with which they are often associated, by the occurrence in the latter of peat and in situ peat pockets.

68. Mudlumps are upwellings of clay that commonly form islands near the mouths of the Mississippi River passes. Morgan and others[69, 15, 107] have summarized the salient features of mudlumps, mapped their distribution, hypothesized concerning their origin, and predicted the areas where they will most probably form in the future. The clay typically forms

slightly elongate, S-shaped islands that may rise to heights of 10 ft above sea level and may reach an areal extent of 20 acres. Fluvial and marine erosion wear away these islands but they are often rejuvenated or new ones may be formed during high water and the accompanying increased discharge of sediment by the Mississippi. Most mudlump islands discharge gas and/or mud through vents or fissures, and glistening, fluid mud may form cones around some vents.

69. Mudlumps consist of clays similar in nearly every respect to prodelta clays. They are believed to have worked upward from deeply buried prodelta clays through overlying coarser deltaic materials (the intradelta sequence) as fingers of mud. It is interesting to note that the Mississippi River Delta is the only area from which these phenomena have been reported, and in the Mississippi River Delta only those passes discharging into deep water, that is, those channels which deposit their load near the edge of the continental shelf, are characterized by mudlump development. Morgan[69] states that "apparently, only in deep water can the bar deposit (the intradelta) become thick enough to exert static pressure of the magnitude necessary for causing flowage within the plastic clay stratum."

70. There appears to be little reason, therefore, for postulating the existence of many of these fingers of mud within the deposits which make up the deltaic plain. Water in which most of the previous deltas of the Mississippi River emptied their load was probably too shallow to have been the site of mudlump formation. They appear to be phenomena associated solely with the present delta.

Intradelta

71. Intradelta deposits are, in essence, the coarse deposits associated with delta advance. At the mouth of a distributary the velocity of its water is checked and the greater part of its load is deposited as distributary mouth bars.[25] Sediments accumulate on the bar crest or are distributed as submerged fans on the seaward sides of the bars. As the distributary is built seaward, it may cut a channel into these coarse materials or the channel may split around the bar. The process is then repeated in each of the smaller channels. Usually one of these distributary channels is abandoned after a time, and the remaining channel enlarges. Distributary channels are initiated not only by bifurcation around bars,

but by crevassing in areas close to sea level where natural levees and stage differences are low. These distributaries deposit coarse material into what may have been quiet waters in which only clays had previously been deposited. Thus, the coarse materials that are preserved as part of the deltaic plain as a delta builds itself seaward are complexly interfingered with clays that settle out in the quiet areas between distributaries.

72. Even the smallest distributary is preceded by waves of coarse intradelta materials; conversely, every area between myriad individual distributaries is a potential trap for interdistributary clays (see paragraphs 76-78). Borings made in the present Mississippi River Delta[25, 107] found reasonably distinct bodies of coarse intradelta, and fine interdistributary materials, the former associated with the major passes, the latter lying between them. The sandy deposits associated with each major distributary have been appropriately called "bar fingers"[107] because they project as definite fingers of sand or sandy silt beneath and immediately to the flanks of these distributaries. The present, "bird's-foot" delta has only a few major distributaries. However, ancient deltas of the Mississippi have had much more numerous and complexly disposed distributaries, the number and complexity appearing to be inversely proportional to the depth of marine waters into which the deltas were built. As mentioned earlier, the Lafourche Delta, for example (see fig. 1), has been called a "horsetail" delta[107] because of its myriad distributaries. Major distributaries were so closely spaced that intradelta deposits form a fairly continuous sandy sequence without intervening clays. Fisk[26] has termed these features "sand sheets."

73. An intermediate situation is represented by the somewhat less complex distributary system of the St. Bernard Delta. Here division of the intradelta from the interdistributary clays is most difficult, but a fairly reliable division of the coarse deltaic from the fine deltaic material is possible. A recent study[111] of soil conditions along possible routes of the proposed navigation channel from New Orleans to the gulf has permitted a fairly detailed reconstruction of the disposition of sediments in portions of the abandoned St. Bernard Delta (see Section E-E', plates 17-17b). In most instances, the position of the intradelta deposits in the

subsurface was found to be marked on the surface by fairly well-defined, abandoned distributaries, and the course from which they diverged. The coarse materials, as in the present delta, are disposed either in a triangular wedge having a flat base and the abandoned distributary at its apex, or as a roughly diamond-shaped deposit that narrows at both the top and bottom in cross section. The most common variation to this general disposition of the coarse deposit is the occurrence of the abandoned distributary along one or the other side of the triangular cross section rather than at its apex. This may be a reflection of bifurcation of the distributary around a bar, shifting the final distributary channel either to the left or the right of the intradelta deposit.

74. Fig. 11 shows the distribution of soil types in more than 300 intradelta samples. Note that nearly 75 per cent of the material is silt or coarser. Sand particles are rarely larger than fine-sand size. The 22 per cent fat clay represents discontinuous lentils of material more properly classifiable as interdistributary clays. However, location of such clay bodies normally requires an inordinate number of closely spaced borings which, except in very detailed soils investigations, would seldom be warranted. The alternative is to distinguish and delineate the body of intradelta deposits. Within this body, clays in roughly the amount shown in fig. 11 can be expected.

75. The distribution of the coarser textured soils in the wedge of predominantly fine soils that make up the fluvial-marine environment is of major importance in exploring soil conditions in the upper 100 ft of the deltaic plain. Although studies of soil conditions for specific engineering projects require detailed airphoto interpretation and a thorough boring program, the general trends of these coarser intradelta deposits coincide with positions of the courses and major distributaries shown in plate 3. In addition, plates 6-6b summarize subsurface data on the distribution of sandy materials based on available boring data. The sands encountered in these borings are believed to be predominantly intradelta materials. However, sands of buried beaches, the bay-sound environment, the nearshore gulf environment and possibly abandoned course, and distributary sands may also be included. As can be seen from these plates, data were available for approximately one-quarter of the study area. Plate 6 shows the areas

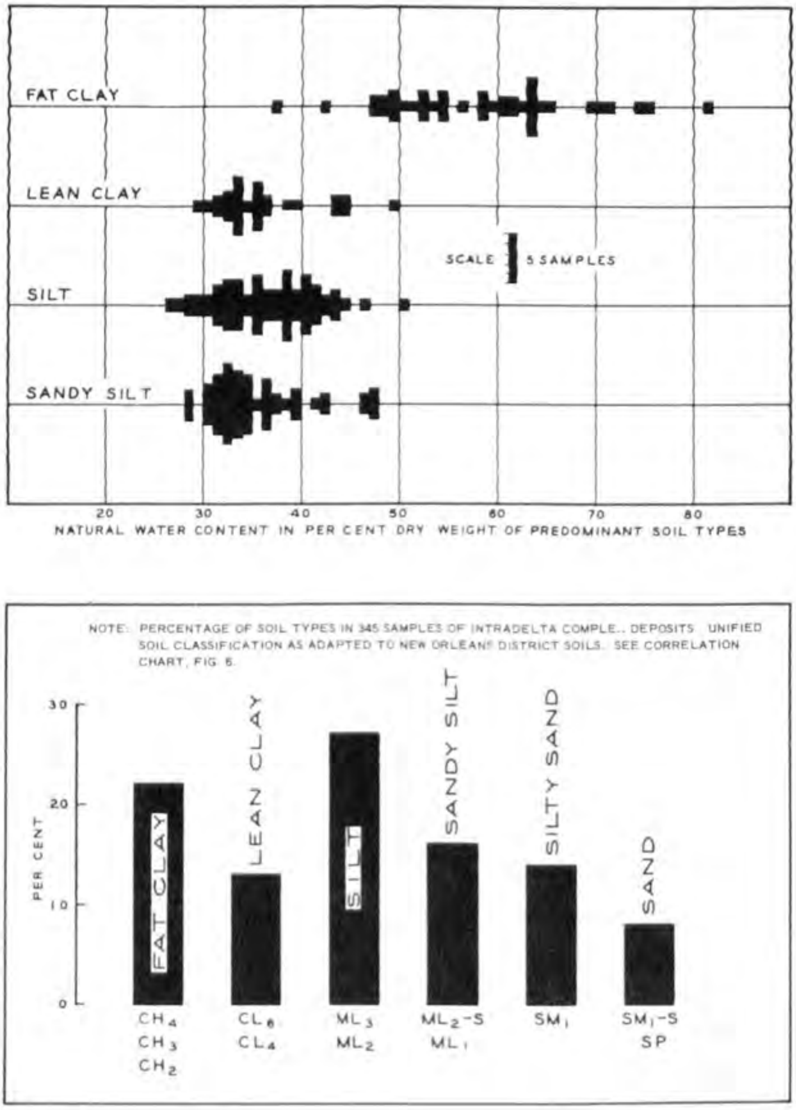



Fig. 11. Selected physical characteristics of intradelta soils

where borings encountered sands at 25 ft, 6a shows the areas where sands are at 50 ft, and 6b the 100-ft-deep sands. Contouring of these sand bodies was impossible since the bodies were often discontinuous, being separated from each other by variable thicknesses of clay. The maps, therefore, show those areas in which sands greater than 10 ft thick were encountered at the depths shown. It should be pointed out that the vast majority of borings used in preparing these plates were shot holes made for seismic exploration. Although only the most reliable of these borings were used, the plates should be used with caution.

Interdistributary

76. Interdistributary sediments are those deposited in the low areas between the distributaries of the present and past deltas of the Mississippi. The typical low-angle bifurcation of the distributary stream gives rise to trough deposits that "V" areally in an upstream direction and widen gulfward. The name "interdistributary" was first applied to the wedges of underconsolidated clay (see paragraph 78) between the major passes of the present delta.[25] Sediment-charged water spilling over subaqueous or low, subaerial natural levees leaves the coarsest sediment near the distributary as part of the intradelta sequence. The finest sediment settles out in the basins between distributaries. Clays discharged at the mouths of the distributaries may also be wafted inland by wave action and settle in these basins. Clays carried overbank by flood flows along the main channel upstream from its branching distributaries may also be deposited in shallow brackish waters between the channel and either active or abandoned distributaries, and thus become part of the interdistributary sequence.

77. Considerable thicknesses of interdistributary clays may thus be deposited as the delta builds seaward. Interdistributary clays often grade downward into prodelta clays and upward into the richly organic clays of swamp or marsh deposits. The line of demarcation between the interdistributary and overlying swamp and marsh clays is particularly indistinct. True marsh or swamp begins when the watery area between distributaries or flanking the main channel has shallowed sufficiently to support vegetative growth. Including this gradation zone with the interdistributary environment results in the fairly large proportion of organic clays shown as characteristic of this environment in fig. 12. Note, however, that approximately 60 per cent of the deposits consist of inorganic fat clays, and that of the 400 samples randomly chosen only about 10 per cent were silt or coarser. Samples used for the preparation of fig. 12 were from the abandoned St. Bernard Delta of the Mississippi. As indicated, cohesive strengths in these materials normally range between 100 and 400 lb per sq ft.

78. Where interdistributary clays rest on prodelta clays the distinction between the two is recognized in carefully logged borings. The silt and fine sand found in the interdistributary environment normally

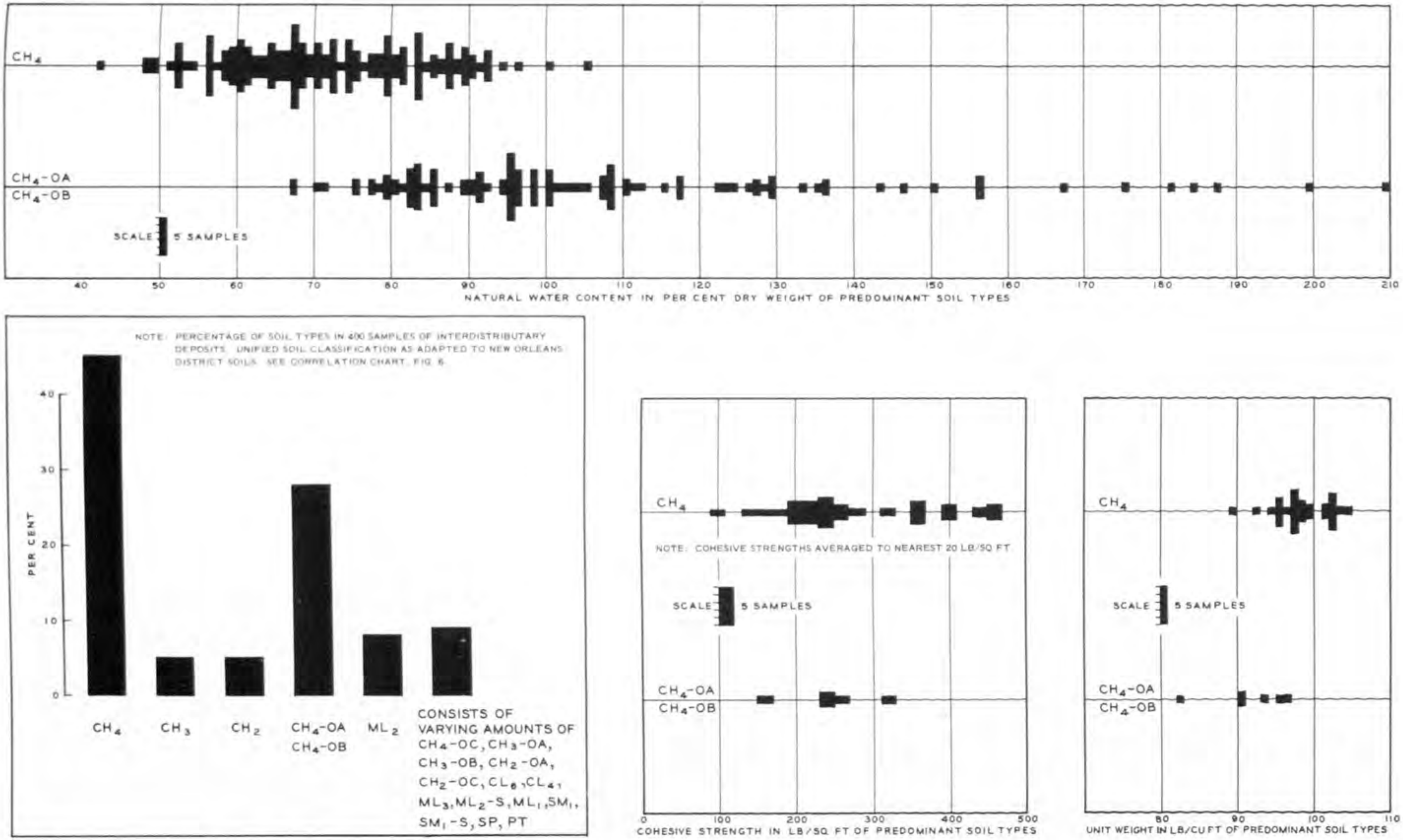



Fig. 12. Selected physical characteristics of interdistributary soils

occur as paper-thin partings between clay lenses only millimeters thick. Cores of these materials often exhibit a varved appearance, the thin laminations of coarser materials undoubtedly representing intervals of overbank flood-flow carrying coarser deposits in suspension. Prodelta clays present a massive, homogeneous appearance with few or no visible planes of parting. Even more striking is the underconsolidated nature of the more recent interdistributary clays. Fig. 13 shows cohesive strengths with depth in a boring off South Pass in the Mississippi Delta. Strengths show little increase to a depth of 375 ft. Beyond this depth strengths are somewhat erratic but show a definite increase. Materials at the point where the boring was taken are identified as interdistributary clays to a depth of 375 ft. Clays below are prodelta. The reason for the straight-line increase of strength with depth in the prodelta clays is that these materials were deposited slowly and were allowed to consolidate normally under load. The overlying interdistributary clays were deposited relatively quickly and are underconsolidated. Although the interdistributary clays have had time to consolidate to a greater degree where they occur in the ancient deltas of the Mississippi, they are, nevertheless, notably lacking in strength when compared with underlying prodelta clays and do not appreciably increase in strength with depth.

## Paludal Environments

79. The paludal environments of the deltaic plain are those characterized by organic to highly organic sediments developed for the most part in situ. The predominant paludal environments are the swamps and marshes, a world half-land, half-water, that seldom rises more than 2 ft above mean gulf level. An estimated 90 per cent of the study area is blanketed by swamp or marsh sediments. Complexly intermingled with the swamp and marsh environments are the lacustrine and tidal channel deposits. Formation of lakes and tidal channels is an important part of marsh development in southeast Louisiana. However, the majority of these features are shallow, insignificant water bodies that leave behind sediments which for all practical engineering purposes can be classified as marsh. A few, however, are

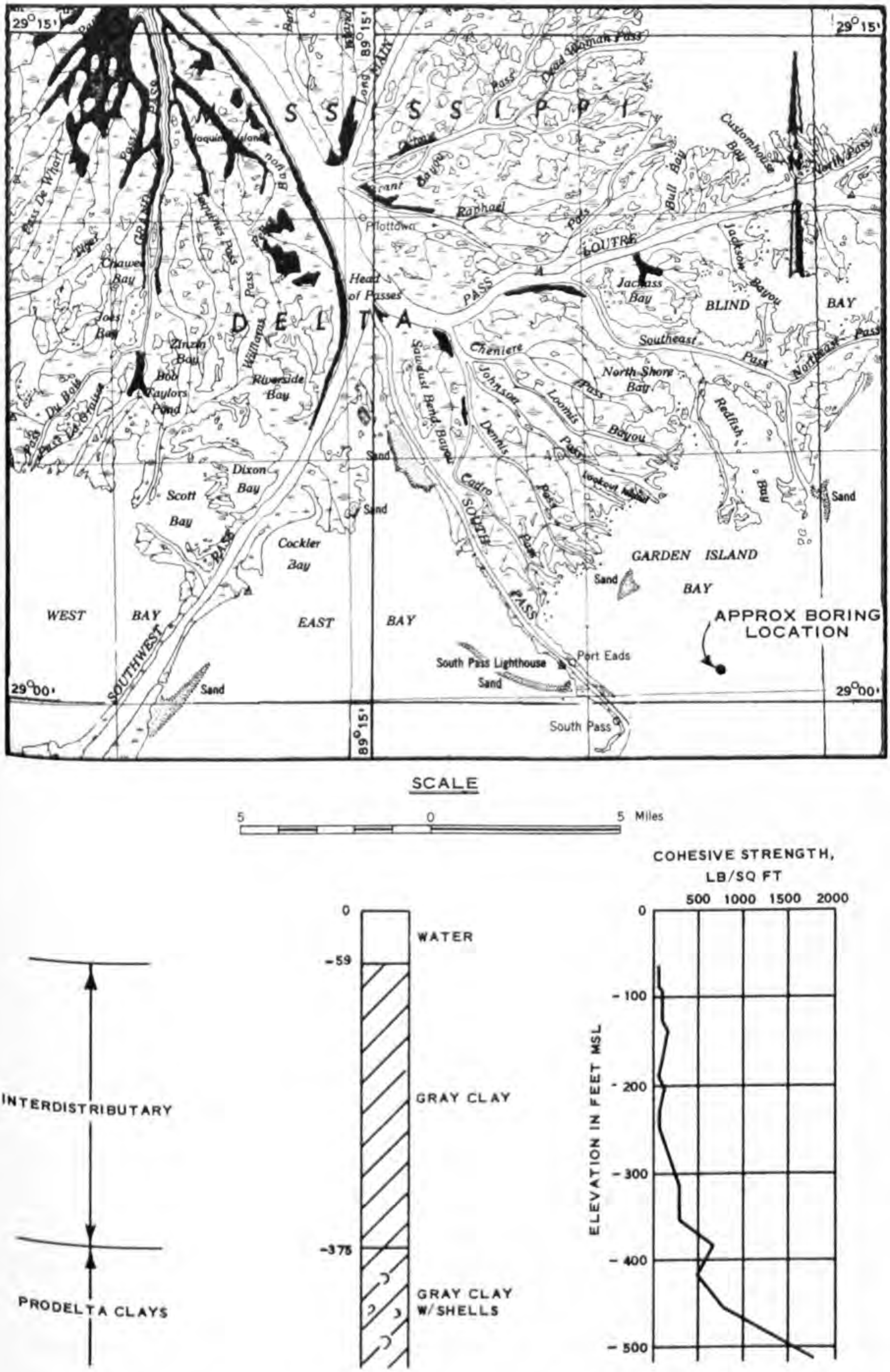



Fig. 13. Strength profile of Recent clays in offshore area

of such size and depth that they form deep channels or lakes during their active stages. On being abandoned, these isolated water bodies fill with distinctive soil types and form important discontinuities in the marsh or the underlying soil sequences.

Marsh

80. More than half the land in the study area is covered with marsh, a nearly flat expanse where the only vegetation consists of grasses and sedges. These may grow in closed formation providing a relatively firm surface underfoot, or the grasses may grow in tufts with mud or water between them. The fairly uninterrupted grassy expanses are called "prairies" by the local inhabitants, the term "marsh" being reserved for the distinctly watery areas. Whether an area consists of unbroken grassy surfaces or of surfaces interrupted by complexly intertwining tidal channels and irregular water bodies is a direct reflection of the amount of subsidence that has occurred, the distance from the zone of active wave attack, and complex biological factors. As the marsh subsides, grasses become progressively more sensitive to increasing salinity. Death of the grasses and "eat-outs" of the marsh by waterfowl leave watery spaces between clumps of marsh grass. These enlarge into myriad small lakes which dot the marsh surface and eventually become connected with an intricate network of tidal channels whose water surfaces rise and fall slightly with the tide.[111]

81. Organic sedimentation plays an important role in the formation of marsh deposits. The marshes are sites for the accumulation of organic materials varying in degree of decomposition. Peats, organic oozes, and humus are formed as the marsh plants die and are covered by water. Normal subaerial oxidation processes are limited, decay is largely due to anaerobic bacteria, and in stagnant water thick deposits consisting almost entirely of organic materials are formed. As a result of consolidation of underlying materials and subsidence of the entire coastal area the marsh surface is, in reality, built "down" rather than "up." In other words, deposition or vegetative growth maintains the surface elevations at a fairly constant level and the marsh deposit thickens as a result of continuing subsidence. Prolonged reductions in the supply of flood-borne or coastal-drift inorganic sediment are recorded in the marsh sequence by peat horizons, for during such periods the marshland surface is maintained principally by

vegetative growth. If reductions become progressively more severe, vegetative growth often fails to keep pace with subsidence and marine gulf waters inundate the coastal marsh zone.

82. Peats are the most common forms of marsh strata. They consist of brown to black fibrous or felty masses of partly decomposed remains of plants in which parts of the original vegetation may be observed.[59] The so-called mucks consist of detrital organic particles carried in by marsh drainage or of vegetative tissues that are completely or nearly completely decomposed. The mucks are watery oozes and can support little or no weight.

83. Sedimentation within the marsh may also consist of considerable proportions of inorganic materials. The nearness to a source of inorganic sediment--sediment-laden marine waters on the one hand and muddy fluviatile waters on the other--is the principal reason for the differences in the types of marsh deposits shown in plate 2 and fig. 14. These inorganic sediments are introduced into the marsh by normal tidal fluctuations of the various channels that drain the flat surface. More important in the introduction of inorganic sediment than lunar tides, however, are the "wind tides" and the "hurricane tides" which can cover the marsh with considerable depths of water. Russell[88] states that during hurricanes the marsh may be flooded to a depth of several feet. Five feet is a rather common depth; depths of 10 ft have been recorded. Clays, silts, fine sands, and organic flotsam are carried tens of miles inland as the hurricane winds pile water on the land. Less spectacular, but probably more effective in the introduction of inorganic sediment over an extended period of time, are the northerly and westerly winds that drive water out of the marshes and the southerly and easterly winds that bring it back. During flood stages of the Mississippi and its distributaries the marsh may be covered with variable depths of fresh water from which Mississippi River clays and silts settle and become part of the marsh sequence.

84. Four marsh types are shown in fig. 14. These types are based principally on individual vegetation units or groups of units shown on O'Neil's[74] vegetation map of the southern Louisiana marshes. There appears to be a reasonable correlation between these vegetation units and the underlying soils. Vegetation is dependent to a large extent on the degree of salinity of the environment in which it grows. Similarly, the soils

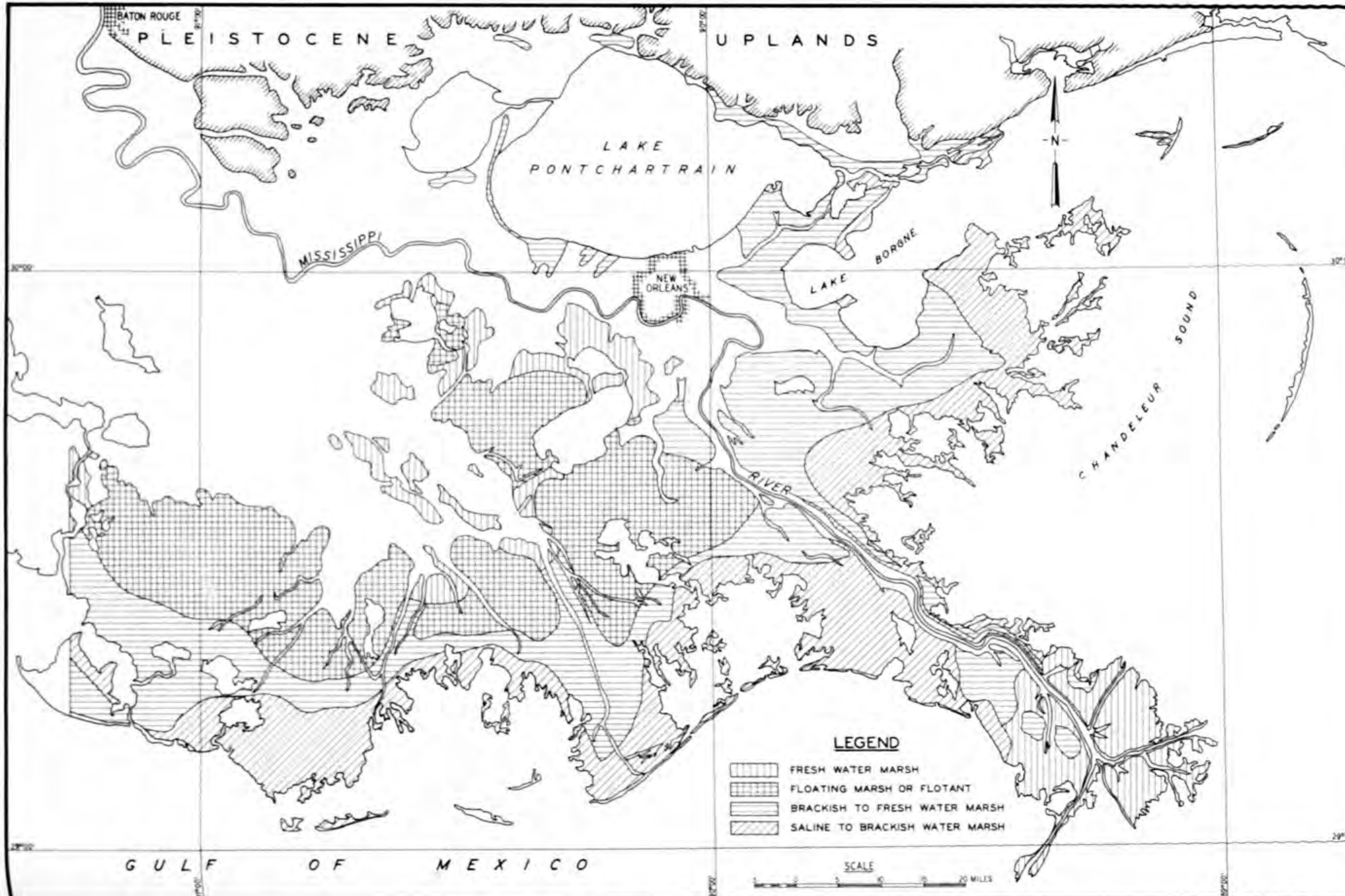



Fig. 14. Distribution of marsh deposits

developed within these environments reflect the proximity of marine sedimentation in a seaward direction and of fluvial, fresh-water sedimentation in a landward direction. A correlation between vegetation and soil units therefore is expected, and future studies should permit subdivision of marsh soils into types considerably more definitive than the four tentative units shown in fig. 14 and discussed in the following subparagraphs.

a. Fresh-water marsh. This marsh type consists of a vegetative mat underlain by clays and organic clays. As mapped it corresponds to O'Neil's zone of Fresh Water Marsh.[74] Modifications were made in its areal extent where bore-hole information dictated. This type of marsh occurs as a band along the landward border of the marshlands and in areas subject to repeated inundation by fresh water. The deposit contains a fairly high admixture of fresh-water clays. An upper foot-thick mat of roots and other plant parts grades into a fairly soft organic clay which becomes firmer and less organic with depth. Peat layers are typical but they are often discontinuous. Organic content is estimated at from 20 to 50 per cent.

b. Floating marsh or flotant. Flotant consists of a vegetative mat underlain by organic ooze. As mapped in fig. 14, it corresponds to O'Neil's[74] zone of Floating Fresh Marsh and Floating Three-Cornered Grass Marsh. Modifications in areal extent were made where available shallow-bore-hole information dictated. The soils sequence of a typical flotant area consists of a mat of roots or other parts of present marsh vegetation with some mixture of finely divided mucky materials from 4 to 14 in. thick. This is underlain by from 3 to 15 ft of finely divided muck or organic ooze grading to clay with depth. The ooze often consolidates with depth and grades into a black organic clay or peat layer. Fig. 15 shows a profile based on Orton[76] in a flotant area south of New Orleans. Note that the organic clay thickens to the southwest reaching a depth of 32 ft. The upper vegetative mat floats on a marsh ooze that reached a thickness of 11 ft. Organic content of this type of marsh is typically high, usually greater than 50 per cent.

c. Brackish-fresh water marsh. The soils sequence consists of a vegetative mat underlain by peat. This type of marsh has been mapped, with some modifications, to correspond to O'Neil's[74] zone of Brackish Three-Cornered Grass Marsh. The soils sequence typically consists of a mat or roots and other parts of present marsh vegetation with some mixture of finely divided mucky materials from 4 to 8 in. thick. This is underlain by 1 to 10 ft of coarse to medium-textured fibrous peat. This, in turn, is often underlain by a fairly firm, blue-gray clay and silty clay with thick lenses of dark gray clays and silty clays high in organic content.

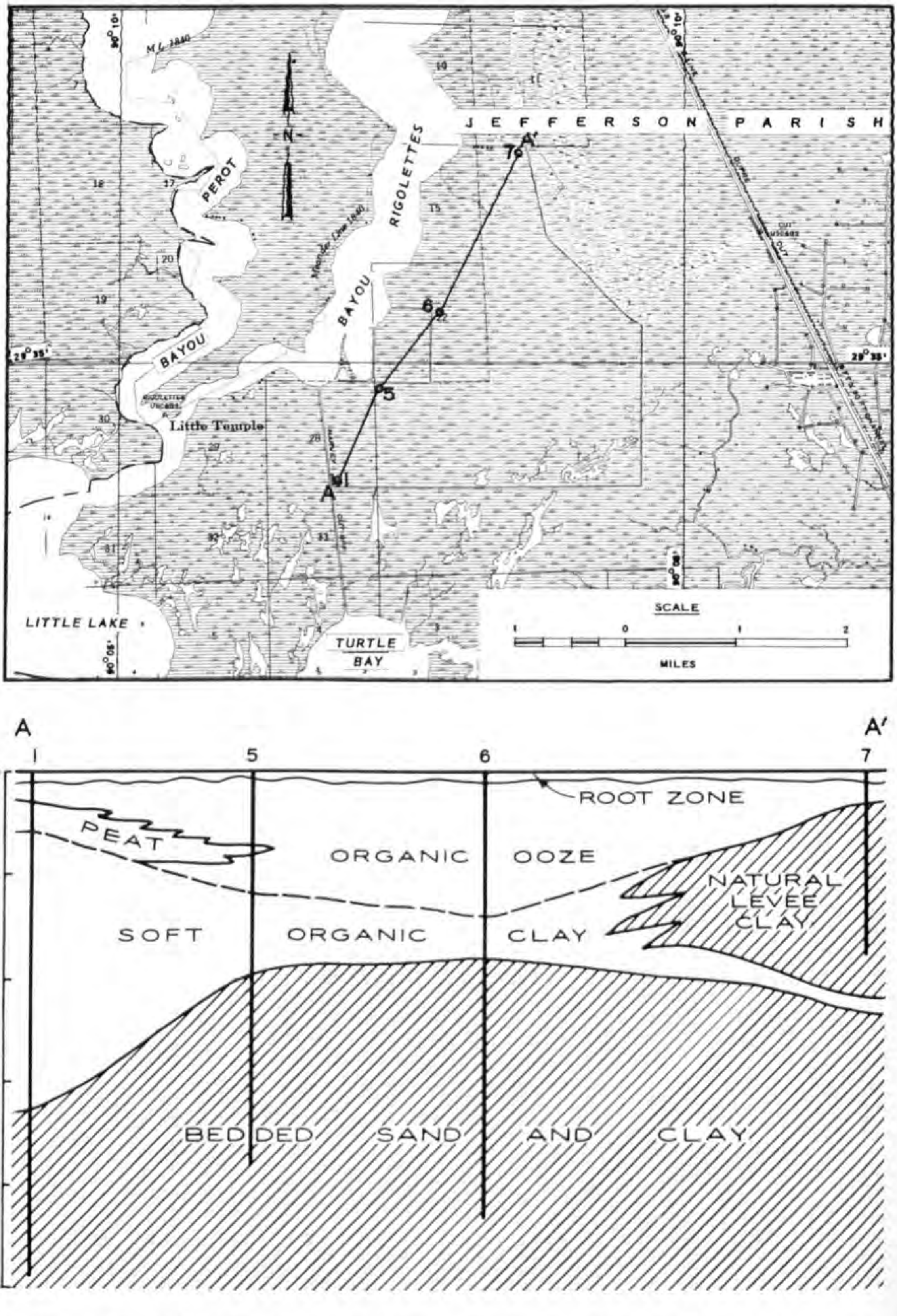



Fig. 15. Typical section in floating marsh or flotant about 22 miles south of New Orleans. Adapted from reference 76

Fig. 16 shows the typical distribution of soil types in some 220 samples of marsh deposits, at least 200 of which were taken from the brackish-fresh water marsh. Note the very high organic content. It is estimated that only 10 to 20 per cent brackish-fresh water deposits consists of inorganic materials. Borings 1D through 49D of section E-E', plates 17 and 17a, illustrate this marsh type. Note the high peat-humus content of these borings as in contrast to the decidedly more clayey organic materials in the ramainder of the section.

d. Saline-brackish water marsh. The soils sequence consists of a vegetative mat underlain by clays. This type of marsh

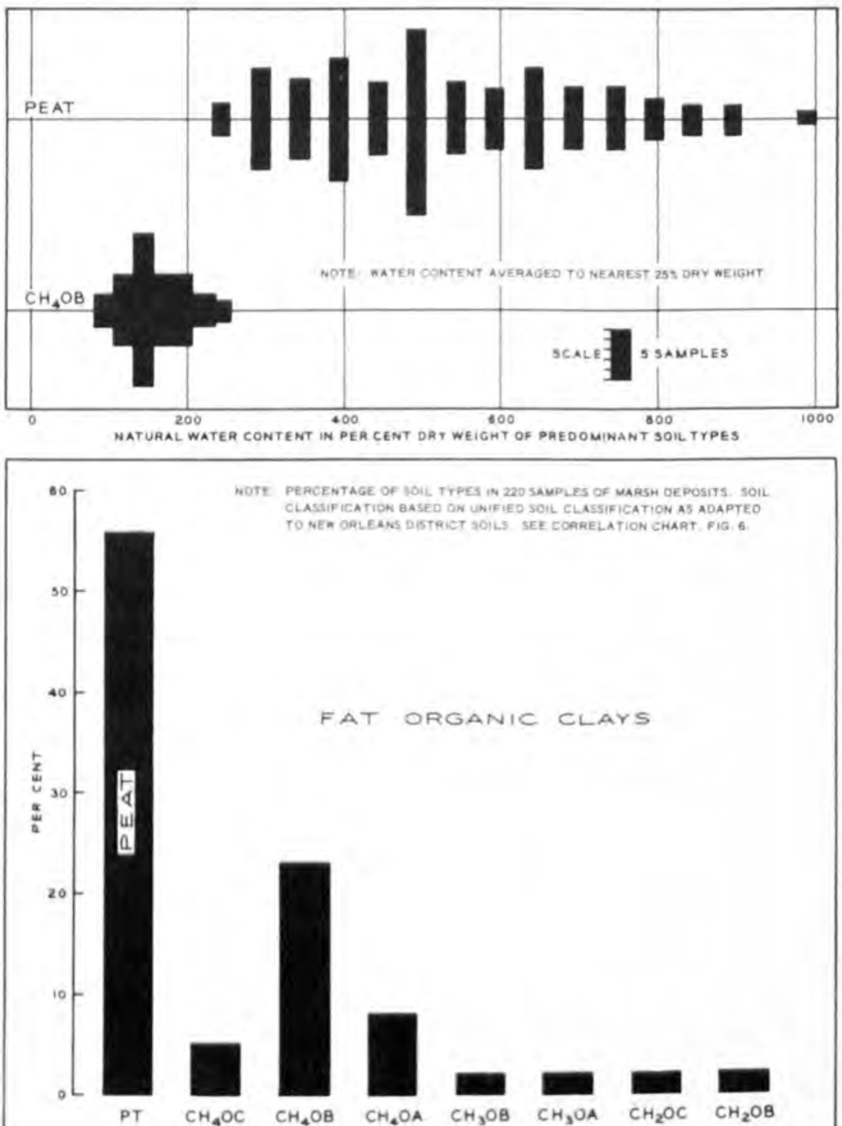



Fig. 16. Selected physical characteristics of marsh soils

was mapped in the study area to correspond with O'Neil's[74] zone of Excessively Drained Salt Marsh. Modifications in areal extent were made where available shallow-bore-hole information dictated. The typical soils sequence consists of a mat of roots, stems, and leaves from 2 to 8 in. thick, underlain by a fairly firm, blue-gray clay with a few roots and plant parts. Tiny organic flakes and particles are disseminated throughout. Clays become less organic and firmer with depth. Saline to brackish water marsh occupies a belt varying in width from 1/2 to 8 miles, flanking the present shore line. In contrast to the other marsh types, a fairly high percentage of inorganic materials imparts some degree of stability to this type of marsh. The silt-fine sand content, particularly near the coast, may range as high as 30 per cent. Organic clays make up an average of 50 per cent of the deposit, and the peat content normally ranges between 15 and 30 per cent. Section E-E', plates 17a and b, illustrates marsh of this type between borings 50D and 63D.

85. Recognition and delineation of the four marsh types described above in southeast Louisiana are based primarily on the vegetation associated with them, vegetation sometimes recognizable in airphotos. Table 2 lists the vegetation characteristic of each type.[113]

86. The general thickness and distribution of surficial peats and highly organic clays, the marsh and swamp deposits, are shown in plate 7. Much of the data used in preparing the map consisted of poorly logged and sometimes widely scattered shot holes, consequently the map should be used with caution. It should also be pointed out that the plate shows the distribution of surficial organic deposits, not those that may be buried by other environments of deltaic deposition. Fig. 17, based on a cross section by Orton[75] shows the subsurface conditions from Houma, La., to the gulf. Note the essentially continuous layer of peat at the base of the section, separated from the surficial peat layer by sandy and clayey material. Too little is known of the history of deposition in this area to permit more than speculation regarding the significance of this lower peat layer. However, it probably represents the subsided marsh surface of one of the older Mississippi River deltas buried by a subsequent wave of alluviation as the Lafourche Delta advanced into the area.

87. Strengths of marsh deposits are very low. The following statements taken from a Transportation Research and Development Command[100] 1954 publication underscore this point:

Table 2

## CORRELATION OF VEGETATION WITH MARSH TYPES IN COASTAL LOUISIANA

| VEGETATION TYPE | | MARSH TYPE | | | |
|---|---|---|---|---|---|
| COMMON NAME | SCIENTIFIC NAME | FRESH | FLOTANT | BRACKISH-FRESH | SALINE BRACKISH |
| Soft rush | *Juncus effusus* | ━ | | | |
| Sawgrass | *Mariscus jamaicensis* | ━ | | | |
| Pickerel weed | *Pontederia cordata* | — | | | |
| Reed cane or Roseau | *Phragmites communis* | — | | ━ | |
| Alligator weed | *Alternanthera philoxeroides* | — | — | | |
| Water hyacinth | *Piaropus crassipes* | — | — | | |
| Water millet or cutgrass | *Zizaniopsis miliacea* | — | — | | |
| Beef tongue or paddle weed | *Sagittaria lancifolia* | — | — | | |
| Elephant's ear | *Colocasia antiquorum* | — | — | | |
| Paille fine | *Panicum hemitomon* | ━ | ━ | | |
| Arrowhead | *Sagittaria latifolia* | — | — | | |
| Bulrush | *Scirpus validus* | ━ | — | | |
| Cattail, lance leaf | *Typha angustifolia* | — | — | ━ | |
| Cattail, broad leaf | *Typha latifolia* | — | — | ━ | |
| Couch or wire grass | *Spartina patens* | | — | — | ━ |
| Oyster grass | *Spartina alterniflora* | | — | — | — |
| Bayonet rush | *Scirpus americana* | | | — | |
| Three square | *Scirpus olneyi* | | | ━ | |
| Leafy three square | *Scirpus robustus* | | | ━ | |
| Big cord grass | *Spartina cynosuroides* | | | — | |
| Saltwort | *Batis maritima* | | | | — |
| Sea oxeye | *Borrichia frutescens* | | | | — |
| Salt marsh grass | *Distichlis spicata* | | | | ━ |
| Sand rush | *Fimbristylis castanea* | | | | — |
| Black rush | *Juncus roemerianus* | | | | ━ |
| Salt-matrimony vine | *Lycium carolinianum* | | | | — |
| Salt water alligator weed | *Philoxerus vermicularis* | | | | — |
| Jointed saltwort | *Salicornia* | | | | — |
| Neddle cord grass | *Spartina spartinae* | | | | ━ |

Note: Thick lines indicate most significant or areally important vegetation types.

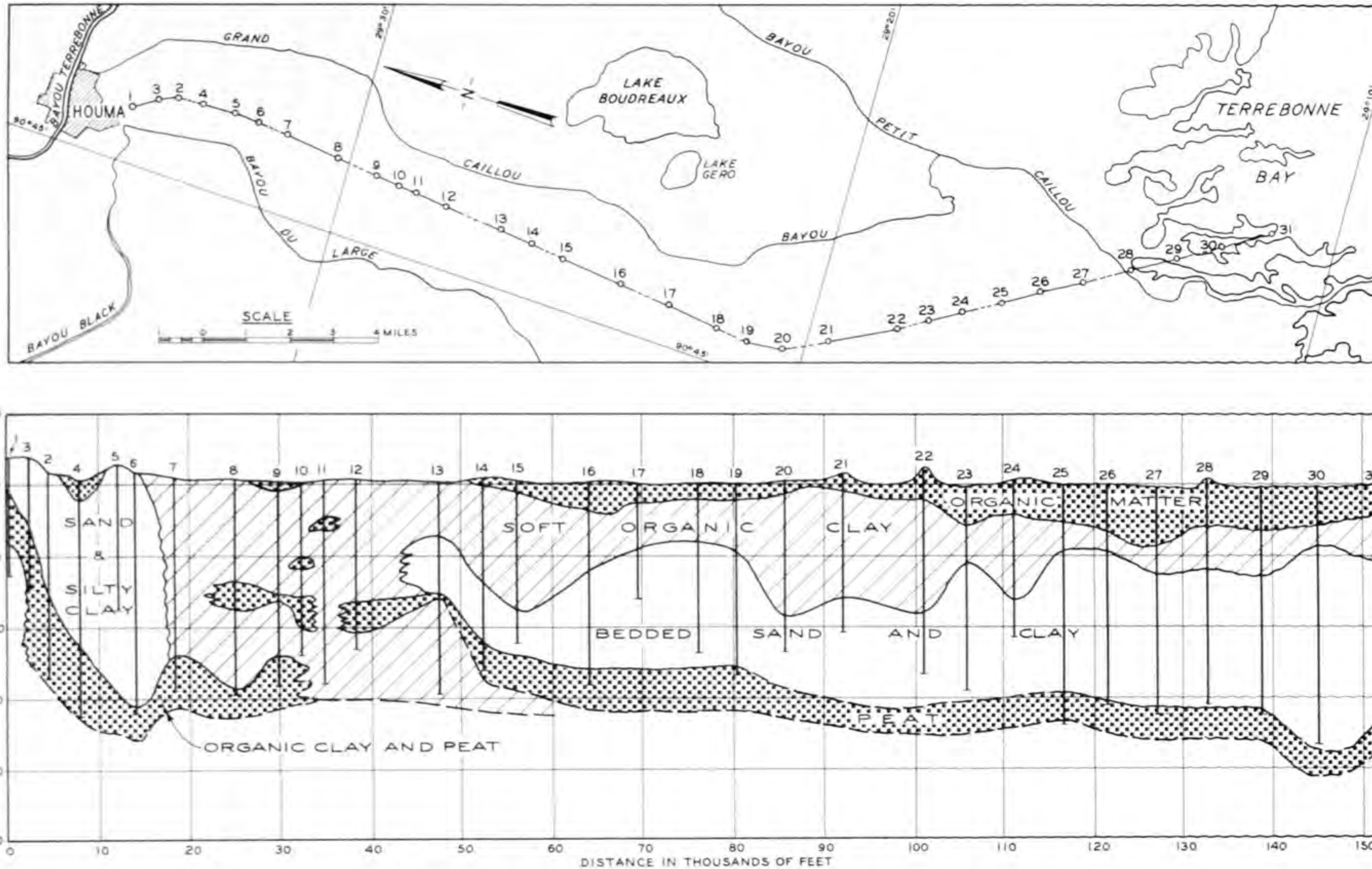



Fig. 17. Profile showing buried marsh layer along proposed Houma Ship Channel. Adapted from reference 75

"Cone penetrometer readings taken in various Louisiana marsh areas during spring months, with a standard Corps of Engineers instrument, gave indices of 10 to 40 as the vegetal mat of 2 to 10 in. was pierced, and indices of 10 to 20 just below the mat, rising to 30-60 at a depth of 6 ft (largely, it is thought, because of friction on the long probe, rather than resistance to penetration of the cone tip). In floating marsh, the instrument, after passing through the mat, quickly sinks to 6 ft under its own weight, indicating indices less than 10.

....The thickness and strength of this mat (over organic ooze) may vary from zero-zero to values which will support 2 or 3 psi of loading, provided it is uniformly applied over reasonable areas...."

88. One of the more striking properties of the high-water-content marsh deposits is their rapid consolidation immediately upon application of a load, such as an embankment. The embankment may subside half its height at the time of placement. Consolidation and subsidence continue for a long period of time at a gradually decelerating rate. In addition, if highly organic materials, particularly peats, are placed in the embankment, shrinkage is considerable. Dodson[17] investigated the shrinkage of Sagittaria peat taken from the marsh and air-dried. His experiments showed that the material shrunk a fourth in vertical dimension and a third in its lateral dimensions so that a 1-cu-ft block extracted in a saturated condition would shrink on drying to a block 9 by 8 by 8 in. or to roughly a third of its former volume.

89. Another common occurrence in excavations in marsh areas is the tendency for the organic oozes, the detrital peats, and soft organic clays to flow laterally into opened cuts. Spoil from cuts must be spread over as wide a base and as far as practicable from the excavation, where such conditions exist.

## Swamps

90. Swamps are distinguished from marshes principally because of the dense growths of trees on the former and their absence on the latter. This is reflected in swamp deposits by the typical occurrence of partially decayed stumps and trunks of trees. Organic content of swamp deposits is high but is generally less than that of marsh deposits. Swamps may be subdivided into a variety of types from the standpoint of vegetation; however, only two types are warranted from the standpoint of the soils sequence

associated with them. These are the inland swamps and the mangrove swamps. Fig. 18 shows their general distribution in southeast Louisiana.

91. Inland swamps. Inland swamps occupy poorly drained basins inclosed by high land of the Prairie Terrace and/or natural levee ridges. These basins receive an abundance of fresh water from overflow of major streams draining an area. The major streams are bordered by well-defined natural levees. The poorly developed drainage within the swamp network, on the other hand, is margined by land only slightly higher and only barely more firm underfoot than that in positions most remote from channels.[88] The general elevation of the most seaward swamp basins approximates that of the marsh. In the more inland swamp areas, those that are seasonally flooded, the general surface is 1 to 3 ft higher, but relief is, nevertheless, imperceptible.

92. As most swamp trees cannot stand even short-time increases in salinity, the gulfward-facing portions of the most seaward swamp basins are transitional to fresh-water marsh, which tolerates salinity for short periods of time. Subsidence permits encroachment of more saline water, thus gradually extending the marsh zone inland in many regions. Thin marsh deposits, therefore, together with their associated and identifying vegetation, may mask a thicker sequence of swamp deposits particularly in the more ancient of the abandoned Mississippi River deltas where subsidence and increasing salinity have killed off all swamp vegetation. Conversely, an actively advancing delta such as that of the present Mississippi, or particularly, the Atchafalaya Delta, may bury marsh beneath swamp deposits. The presence of logs, stumps, and aboreal root systems in the swamp deposits usually permits their identification, and their continuity in plan can be estimated from the position of the major course or distributary which they once bordered and which supplied their inorganic content.

93. Fig. 19 summarizes physical data collected from 50 samples of inland swamp deposits. The samples were classified according to their sand-silt-clay ratios and their organic content. Atterberg limits of the three predominant soil types are plotted on a plasticity chart in fig. 19. Note that most of the soils are classifiable as fat clay (CH) under the Unified Soil Classification System; some of the samples, particularly the highly organic clays, fall below the A-Line and would be classified as

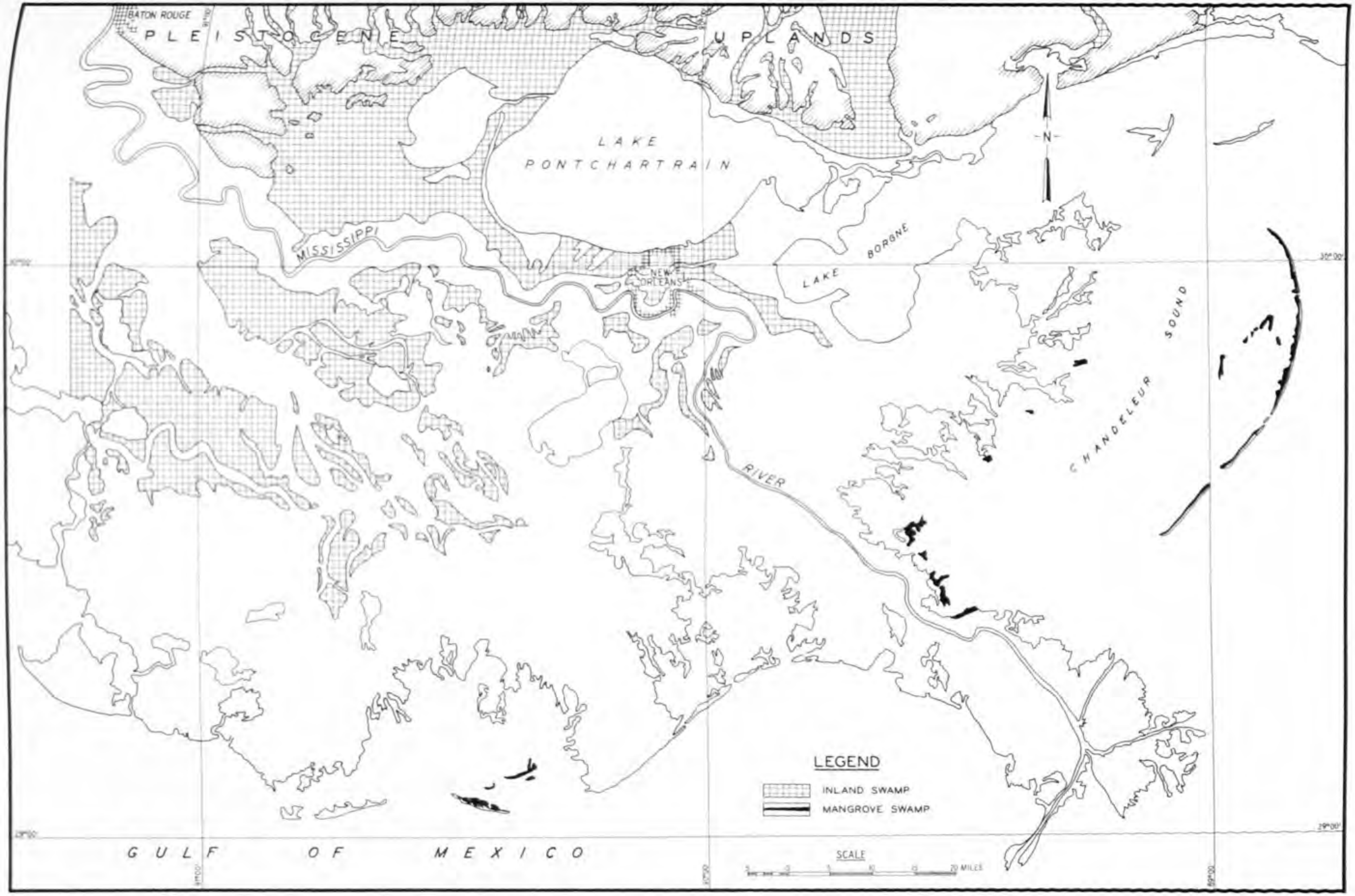



Fig. 18. Distribution of swamp deposits

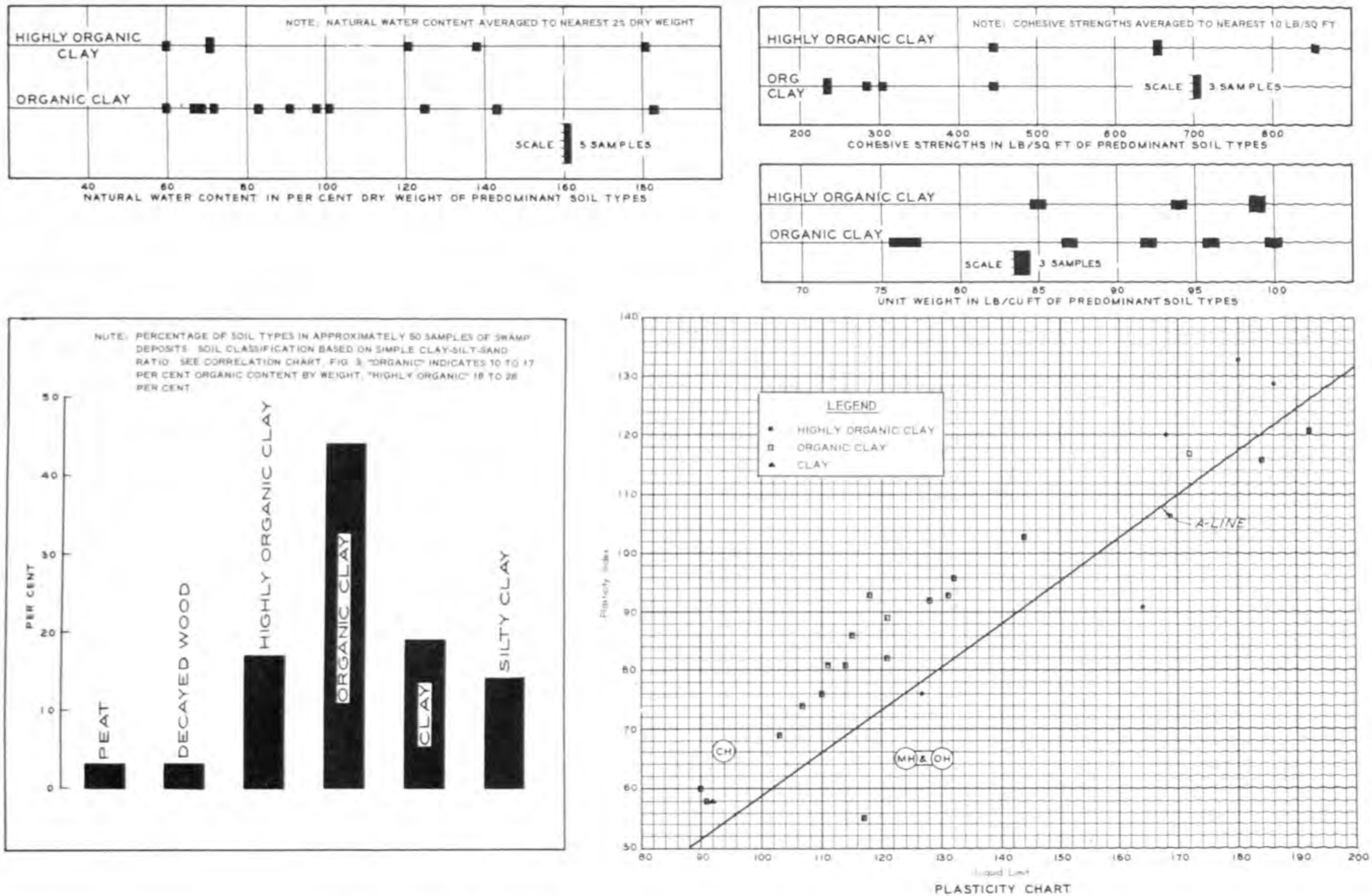



Fig. 19. Selected physical characteristics of swamp soils

organic clays (OH). Based on the samples analyzed, organic content of swamp deposits is normally less than 30 per cent. Organic material occurs principally in the form of organic and highly organic clays, however, peat and layers of decayed wood are not uncommon. Inorganic content is a reflection of the proximity of the stream that supplies, or once supplied, clays during overbank flow, and organic content can be expected to increase and the inorganic content to decrease with distance from such a stream. Blocky peat from 3 to 10 ft thick in which fragments of tree trunks are still distinguishable have been reported[59] from southwest Louisiana where the land is relatively high and the influx of inorganic sediment is negligible. These, however, appear to be the exception rather than the rule. Water contents of the predominant highly organic and organic clays are shown in fig. 19. Cohesive strengths and unit weights of a limited number of samples are also shown. Section B-B', plate 12, shows a typical swamp sequence overlying marsh deposits just south of Lake Pontchartrain.

94. Mangrove swamps. Mangrove swamps are salt-water swamps. The main areas of black or honey mangrove (Avicennia nitida) swamp are found on Timbalier Island, west of the present Mississippi Delta, and Freemason, North, and Chandeleur Islands to the east. In some places, especially flanking Chandeleur and Breton Sounds, mangrove fringes the marshland shore line. Russel[88] points out that within the St. Bernard marsh, long belts of low mangrove bounded on either side by marsh grasses indicate the presence of submerged natural levees. The island growths are exemplified by the Chandeleur Islands, where a dense, tangled, mile-wide expanse of mangrove, 2 to 3 ft in height, flanks the beach to landward. The retreating beach buries the mangrove and, as retreat continues, their stumps are exhumed in the foreshore beach zone, thus attesting to the rapidity of beach encroachment. The more inland growths seldom exceed 4 ft in height. However, Brown[7] notes that in Plaquemines Parish where fresh water from the Mississippi River empties into Bayou Tortillion via the Ostrica Canal (29°20'N, 89°30'W) mangrove reaches a height of 20 to 25 ft, the largest black mangrove seen in Louisiana.

95. A typical soil sequence in the mangrove swamp consists of a thin layer of dark gray to black, very soft, organic silty clay covering and forming the matrix for a tangled, interlocking root zone which averages 5

to 12 in. in thickness. Numerous cylindrical pneumatophores (tuberlike extensions of the roots) arise on the roots to project above the surface for a few inches. Few data are available on the thickness of the mangrove swamp deposits. A thickness of at least 5 ft of organic-rich clays, silts, and sands should be expected, however.[111]

96. The sequence on barrier beaches should be somewhat different than that where the mangrove fringes the mainland. On the barrier beaches, the mangrove takes hold on the sandy washover fans formed on the inner side of the beach as storm waves breach the beach area. Silty and clayey materials are incorporated with these washover sands and the mangrove begins to grow. The growth, in turn, entraps more clayey materials from the protected waters and a sequence of sand to organic clay sand and eventually organic clays is developed, all mixed with shell material. The soils sequence from the surface down, therefore, is organic clay, organic clay-sand, and organic sand and silt. Shell content is relatively high.

Lacustrine

97. Lacustrine deposits of the deltaic plain are considered part of the paludal environment of deposition because lake formation is normally a stage in the deterioration or partial burial of the marsh. Lakes vary in size from small marsh ponds, a few feet in diameter, to large marshland water bodies such as Lake Salvador, which is approximately 13 miles long and 6 miles wide. Lake Pontchartrain, which is not a true marshland lake, is 40 miles long and 25 miles wide. The smallest marsh lakes have maximum depths of approximately 1.5 ft; whereas the largest marsh-inclosed water bodies reach depths of 8 ft. Lake Borgne and Lake Pontchartrain reach depths of 10 and 15 ft, respectively. For purposes of discussion, lakes are divided into (a) small inland lakes, (b) transitional lakes, and (c) large inland lakes.

98. Small inland lakes. Lakes within the marsh are formed as a result of subsidence and by erosion from wind and hurricane tides. They often occupy topographic "lows" formed by locally interrupted drainage, surficial burning, animal "eat-outs," etc. After a body of standing water is established the waves created by the wind initiate a winnowing action which concentrates the coarser material in the deepest portion of the lake. While these lakes are relatively small--as much as a mile or so in

diameter--they are no more than water-filled depressions in the underlying marsh surface. Depth of water may be only slightly more than one foot and the bottoms are often covered with fine oozes that overlie the original peat or organic clays of the underlying marsh. These oozes are described as rubbery or jellylike masses that will stand 6 or 8 in. high on the blade of a shovel and hang together in the face of considerable vibration. They appear to be composed largely of clay and organic colloids or emulsoids. In many places they reach a thickness of 2 to 3 ft.[88, 105] Hundreds of such lakes dot the marsh surface in southeast Louisiana. Normally, as subsidence continues, these lakes develop typically circular outlines and grow in size. Where floating marsh grasses occupy a lake the area may eventually revert once again to marsh.

99. Deposits associated with small inland lakes are thin and for all practical purposes may be considered as part of the marsh. They are so mapped in plate 2. Fig. 20 shows the general distribution of the largest of the myriad small inland lakes which, because they are so numerous and intricate, have been mapped in plate 2 as marsh or swamp.

100. Transitional lakes. Because of subsidence and other factors, lakes typically become larger and more numerous near the shore line of the deltaic plain. As the shore line retreats lakes just inland are breached and lake waters are free to move with the currents affecting the adjoining open water of the bay or sound areas. Fines winnowed from the bottoms of once-inclosed lakes can be moved seaward and the lake bottom deepens and becomes carpeted with the coarser materials left behind by the winnowing action. Deposits in such areas are thus transitional between the organic fines found in the inland lakes and the largely inorganic silty and sandy materials found carpeting the bays and sounds (see paragraphs 113-119 for discussion of bay-sound environment). The major transitional lacustrine environments are shown in fig. 20. Comparatively few data are available on the soil types most characteristic of this environment. However, materials have been reported[88, 103, 15, 111, 55] ranging from fine sand and shell to jellylike oozes. An important consideration is that these deposits are transitional and in the normal sequence of deltaic plain development are incorporated with the coarser bay-sound deposits of the offshore areas.

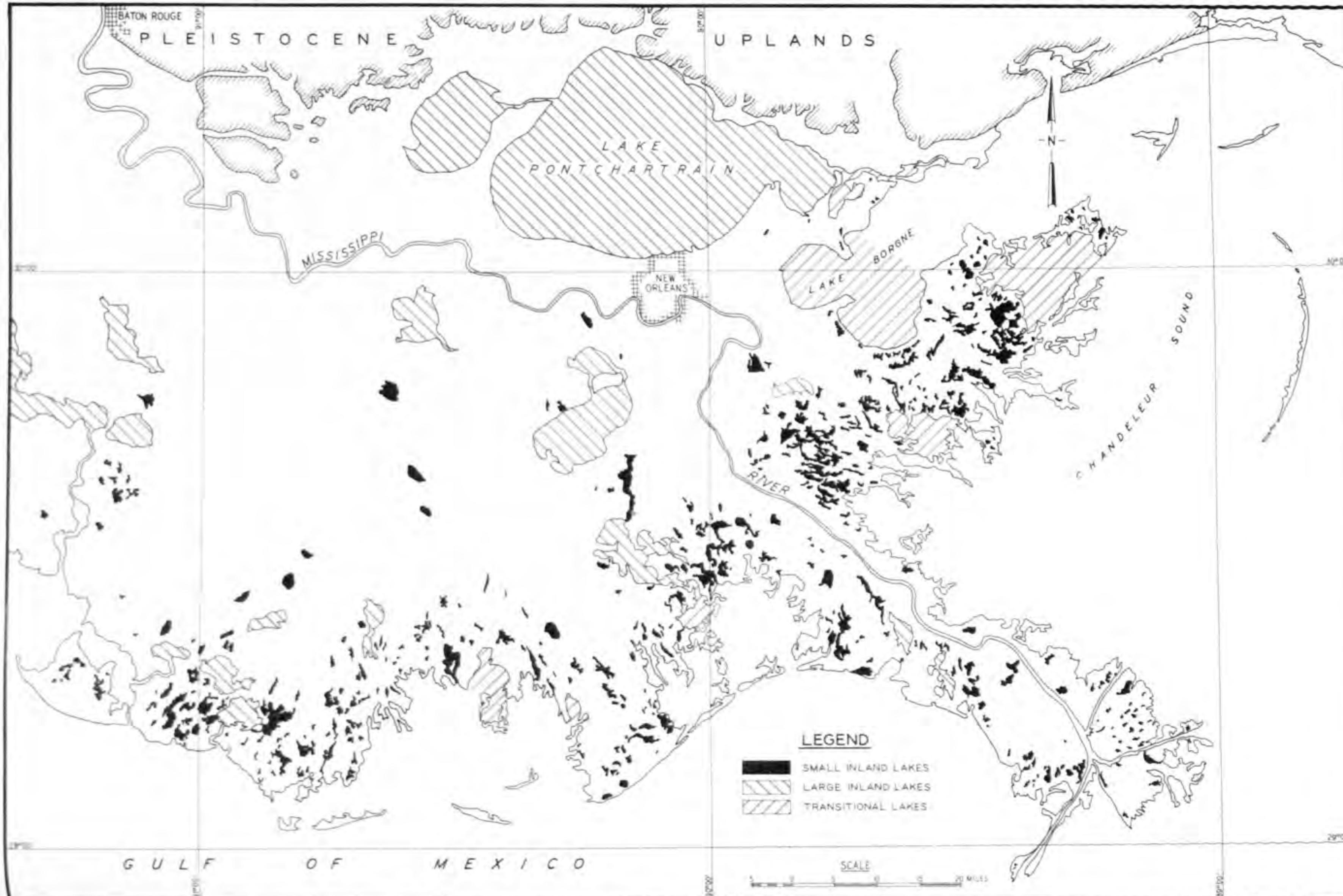



Fig. 20. Distribution of lacustrine deposits

101. Large inland lakes. Large inland lakes appear to be the only lacustrine sites where materials are deposited in significant amounts. The present areas of large inland lake deposition are shown in fig. 20. Very little is known of the distribution of such deposits that may now be buried beneath marsh; however, lacustrine clays undoubtedly form a reasonable proportion of the upper 20 to 30 ft of the deltaic plain.

102. Factors involved in the growth of inland lakes that initiate as depressions in the marsh surface are complex. Impounding of water through distributary growth, faulting, and subsidence under the influx of clayey sedimentation from nearby alluvial streams may, singly or in combination, bring about the formation of a large inland lake. Price[81] in a study of inclosed and partially inclosed water bodies along the Gulf Coast, has pointed out the relationship of the average width of a particular water body to its depth--the greater the average width, the greater the depth. This, he states, is good evidence that the fetch, or distance of translation of wave motion and its causative agency, the surface wind, is directly proportional to wave depth and determines the depth of effective wave scour. The width of the open part of a particular water body determines the fetch, and the depth of the water body is the result of average wind velocity and wave scour. If this is true, there would be a limit to the size of inland lakes dependent on their depth. Increase in depth could only be brought about by (a) subsidence and/or (b) wave scour of the lake bottom and removal of material. Material could be removed through tidal channels or by its piling up in low ridges about the periphery of the lake. Undoubtedly both subsidence and removal of material are important in enlarging inland lakes. Enlargement may be halted by a predominance of sedimentation over these two processes. Deterioration may be brought about by stream diversion into the lake or the formation of a floating vegetative mat on the lake surface.

103. Growth or deterioration of large inland lakes appears to be a relatively slow process. Comparison of mapped shore lines at various dates shows little change in the outlines of the larger lakes except in areas of rapidly changing alluvial sedimentation such as the Atchafalaya Basin. Although no instances have been documented of the complete filling in and abandonment of a lake in southeast Louisiana, there is little doubt that lacustrine clays, now completely masked by marsh, form part of the deltaic

sequence. Few reliable data are available concerning the type of sediment underlying such large inland lakes as Salvador and Lac des Allemands, but closely spaced and fairly well logged shot holes in Lac des Allemands record a consistent layer of organic "muck" of lacustrine or lacustrine-marsh origin ranging from 7 to 12 ft thick. Treadwell[103] has pointed out that lake sediments seldom show any trace of bedding. Deposition is rather slow and the sediments contain many polychaetes and mollusks which continually destroy any bedding that is developed.

104. Good data are available on the thickness and physical properties of the lacustrine materials that underlie Lake Pontchartrain. The data, however, are not necessarily representative of materials underlying other large inland lakes. Lake Pontchartrain is believed to have been a former marine water body that was completely or nearly isolated from the sea by the northward extension of the Metairie distributary now marked by the natural levee ridge that trends northeastward through New Orleans toward the Prairie Terrace highlands (see plates 1 and 2). The water body thus impounded probably filled rapidly for a time, particularly while the Metairie distributary was active, then more slowly from periodic overbank flow of the established main stem of the Mississippi River. A fairly recent stage in its development is believed to have been the establishment of the deep channel through the Rigolets into Lake Borgne and Mississippi Sound through which fines could be carried seaward. Although controversial, indications are that the rate of subsidence and removal of material through wave scour are slightly greater than deposition in the lake of material carried into it through alluvial processes, and that Pontchartrain and Lake Maurepas to the west are both gradually enlarging.[88]

105. Bottom sediments in Lake Pontchartrain as well as the character of these sediments with depth have been tested. Steinmayer[97] indicates that clays form the bottom in the central and western portions of the lake while a band of silty and sandy material flanks the northern, eastern, and southeastern shores. He points to the existence of an extensive sand and oyster shell reef on the northern side of the lake. Since oysters are not found in the lake today he suggests their former presence indicates that once much more saline conditions existed in the lake, at a time when the area was still a relatively open arm of the sea. The brackish water clam,

Rangia cuneata, is the dominant form of molluscan life found in the lake today.

106. Section C-C', plates 14 and 14a, shows the distribution of the deposits beneath Lake Pontchartrain in profile. A very consistent clay to clay silt forms a stratum from 20 to 30 ft thick beneath the entire lake. The deposit thins gradually northward overlying Pleistocene or weathered Pleistocene deposits. Southward it overlies sandy bay-sound deposits and merges laterally southward beneath New Orleans with prodelta clays. Although it might be argued that the lowermost of the clays designated as lacustrine on the section are probably prodelta clays spread out before the Mississippi River as it advanced into the area, there is no lithologic or physical break apparent in the deposit. Most of this fairly homogeneous clay stratum is believed to have been deposited in a strictly lacustrine environment. Fig. 21 summarizes some of the physical properties of these lacustrine clays. The predominant soil textures, based on a clay-silt-sand ratio classification, are clay and silty clay. According to the Unified Soil Classification System, all samples analyzed (see plasticity chart in fig. 21) are fat clays (CH). Cohesive strengths of the lacustrine soils are low, ranging from 50 to 200 lb per sq ft. Natural water contents are high, ranging most commonly between 70 and 150 per cent dry weight.

Abandoned tidal channels

107. Relatively little is known about the process of tidal channel growth and abandonment in the deltaic plain. Literally thousands of tidal channels exist in the area. Some are minor and insignificant, others are deep (30 ft), wide (400 ft) channels which if abandoned and filled would form major and significant prisms of soil within the deltaic plain. Indications are that the process of tidal channel abandonment and fill is relatively rare in the deltaic plain. The trend appears to be for the many small lakes connected by tidal channels to gradually enlarge and encompass the channels, the channels losing their identities. There are instances, however, where the sinuous outline of a tidal channel, now completely filled with sediment, can be plainly seen on aerial photographs. Since such areas can be expected to rapidly develop a vegetative cover fairly indistinguishable from the surrounding marsh, there is no way of estimating

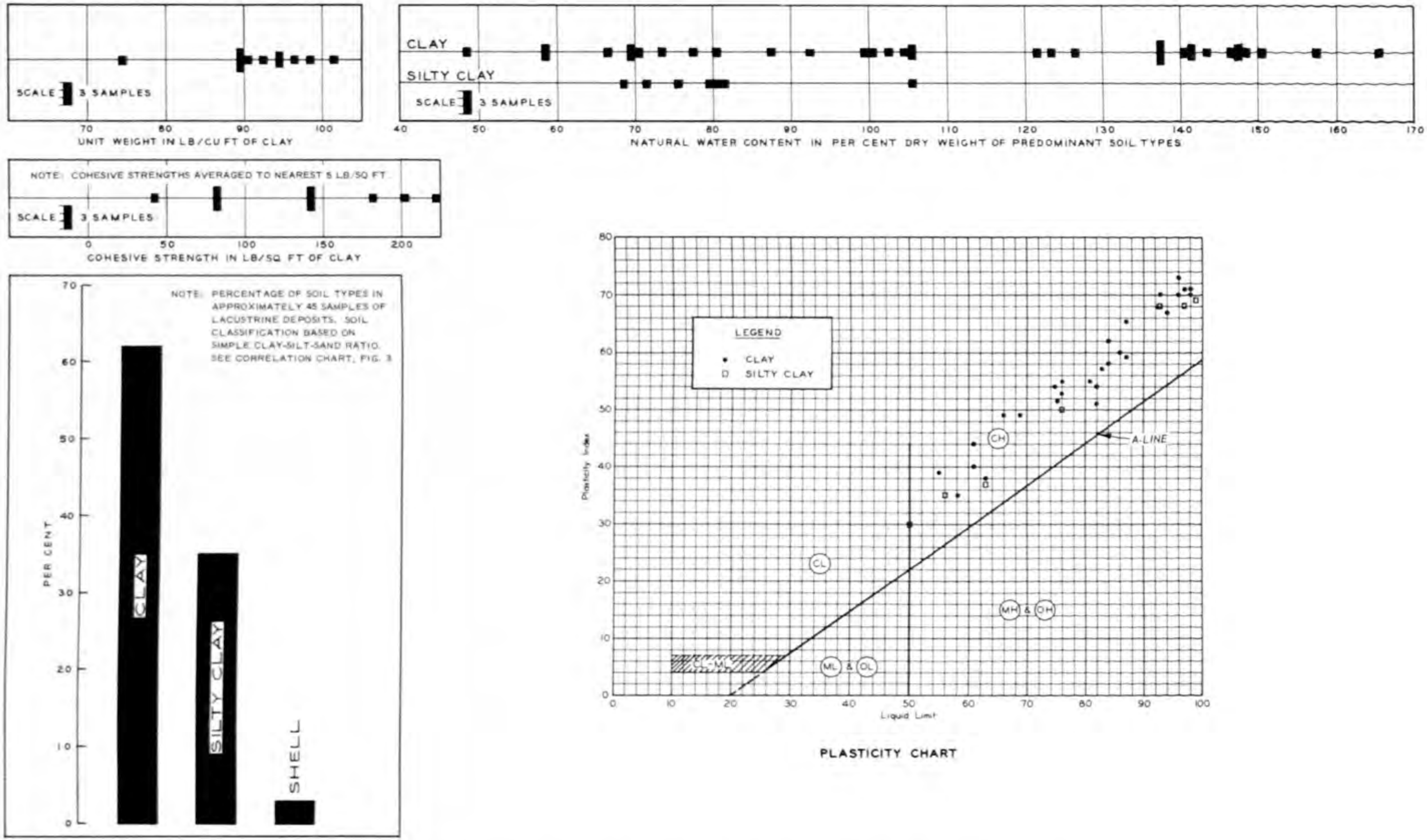



Fig. 21. Selected physical characteristics of lacustrine soils

the number of filled tidal channels that may be masked by marsh deposition in the deltaic plain.

108. Within a flat, homogeneous marsh region, the width and depth of a tidal stream are primarily a function of the velocity and volume of water forced back and forth through the channel with the rise and fall of the lunar tide. The volume of water available is, in turn, dependent on the size of the marshland area or water bodies drained by the stream. In general, therefore, streams draining large areas and/or lakes will be wider and deeper than those draining small tracts and/or ponds. A factor which periodically affects tidal streams is the depth of marshland inundation resulting from hurricanes, wind tides, and floods. When water swept inland by abnormally high wind or hurricane tides returns to the gulf, tidal channels are scoured below their normal depths. Deepening depends on the depth of inundation (volume of water) and also upon the suddenness with which the hurricane or southerly winds cease--if the forces cease abruptly the velocity, and consequently the erosive power, of the returning water will be greater. Although this scouring action is not of equal intensity along the entire bayou course, spot increases in bottom depth of 4 and 5 ft have been recorded. The deepening is temporary, however, for the stream soon refills to a depth compatible with normal tidal flow. As a result of this process the bottoms of tidal bayous are covered with a discontinuous ribbon of soft channel fill of fat clays ranging up to 5 ft in thickness.

109. The hydraulics involved in the abandonment of a lengthy segment of a tidal channel are poorly understood. The most comparable situation for which some data are available is the abandonment of distributary channels of the Mississippi River. Indications are that when such distributaries are abandoned they choke with sediment--the coarser sediment available from suspended or bed load--immediately downstream from their junction with the main stream. Downstream from this point the abandoned distributary remains as an elongate open body of water for very lengthy periods during which it gradually fills in with sediment. Such a process probably is active in the marsh areas, but because sediment supply is smaller and energy expended by tidal streams far less than their fluvial counterparts, the process should be considerably slower.

110. Tidal channels typically develop sinuous meanders. Migration

of these meanders, however, appears to be negligible. Comparison of Coast and Geodetic charts of coastal areas covering a period of 50 years shows little over-all change in the position or size of most of the broad loops of the more prominent tidal channels. Subsidence may have incorporated some of the channels into lakes but their actual migration is limited. Migration of tidal channels, however, even though limited, is an established fact. Treadwell[103] in studying the development of tidal channels emptying into Chandeleur Sound and adjoining waters presents some interesting information on tidal channel migration. Tidal accretion deposits occasionally form on the insides of bends, and meander loops are cut off from the main stream and form tidal ox-bow lakes. In much the same fashion as happens in cutoffs on alluvial streams, the severed loop plugs with the coarsest material available at the points of cutoff. Only the finest materials settle out in the remaining portion of the loop. A tidal cutoff in south central Louisiana was filled with a blue-gray homogeneous clay wedge 23 ft thick, having a median grain diameter* averaging 0.002 mm. Organic content averaged only about 3 per cent. Water contents ranged between 120 and 155 per cent dry weight. Liquid limits ranged between 107 and 145; the plasticity index ranged between 78 and 117.

111. The number of samples available of tidal channel fill are too few to determine any characteristic ranges of physical properties. The few examples available are fat, fine-grained, well-sorted clays. However, the organic content in the fill material may vary considerably depending on the proximity of a source of inorganic sediment or whether it fills an abandoned loop or a much more lengthy segment of the tidal channel. Organic matter incorporated with tidal channel fill can be expected to be largely detrital and dispersed in small fragments throughout the fill. It is carried in as discrete particles by tidal flow or storm waters and thus becomes incorporated with the inorganic fill as an alluvially transported sediment. Root structure and peat pockets or lenses, characteristic of the marsh, are rare, depending on the occasional introduction of some large organic particle washed in by storm waters or by the death of floating

* Median grain diameter is the grain size at which 50 per cent of the material is larger and 50 per cent is smaller.

marsh vegetation. The significant point is that tidal channels are sometimes abandoned in the deltaic plain, and where this occurs, they can be expected to be filled with materials quite distinctive from the surrounding marsh deposits.

## Marine Environments

112. The four principal environments of marine deposition in the study area are (a) the bay-sound, (b) the reef, (c) the beaches, and (d) the nearshore gulf. These deposits are formed exclusively under marine conditions: the beaches and the reefs largely through marine deposition; the bay-sound and the nearshore gulf, because of marine erosion, through the winnowing and sorting action of the waves. Materials associated with each of these environments are being deposited only in the shallow coastal waters today and their areal distribution is fairly limited (see plate 2). However, they form important portions of the subsurface soils incorporated in the deltaic plain.

### Bay-sound

113. As the name implies, the bay-sound sequence carpets the floors of the bays and sounds--areas partially protected by barrier beaches or coastal restrictions, but nevertheless with sufficient open water so that waves of considerable size and scouring capacity can rework the underlying deltaic and marsh deposits. Fines are sorted and carried either inland or out to deeper water; the coarser fraction, sands, silty sands and silts, settles back to the bottom where it is intermingled with the shells of organisms living in the bay-sound waters.[111]

114. Plate 2 shows the distribution of the bay-sound environment in the shallow offshore waters of southeast Louisiana. This environment borders directly on the gulf and is typically separated from it by narrow barrier islands. Landward, there is a transition from bay to marshland lake. In outline, therefore, the environment exhibits a relatively smooth arcuate outer boundary and a jagged inner margin. The size of the bay-sound water bodies varies from small bays a mile or two in diameter to expanses of water, such as formed by the combined Chandeleur-Breton Sounds, which reach 50 miles in length and 15 to 25 miles in width. A distinction

as to which of the intricate bays along coastal Louisiana should be included in this environment is an arbitrary one. In general the environment is mapped in plate 2 only in the larger of the bays where a distinctive coarsening of bottom deposits can be expected in contrast to the bordering organic and fine-grained lacustrine and marsh deposits. Except in outlet channels, where depths of over 100 ft are sometimes found, the bays are seldom more than 5 to 6 ft deep. Depths in the sounds vary from 5 to 25 ft; however, a depth of 8 to 12 ft is typical.

115. Bay-sound sediments dip gently gulfward, thickening in this direction, and grade into nearshore gulf deposits (see discussion of the nearshore gulf environment, paragraphs 139-141). They range in thickness from 3 to 20 ft, averaging 10-15 ft. Plate 16 shows the typical distribution of bay-sound deposits in profile in Chandeleur Sound. Reference 111 contains a number of subsurface sections detailing the soil types found in this environment in the same area. The seaward limit of present bay-sound deposition is easily definable since it is marked by barrier beaches. Maximum bay-sound development occurs where the land areas behind the barrier beaches have subsided and the shore line has retreated at a much faster rate than the landward movement of the beaches. Buried bay-sound deposits can also be expected within the mass of deltaic plain sediments (see plates 10 and 13). The most probable occurrence of such buried sediments is behind the areas of known or probable buried beach occurrence. The location of buried beaches is discussed in paragraph 134 and illustrated in fig. 25.

116. Fig. 22 summarizes the distribution of soil types in 35 borings penetrating the bay-sound sequence in Chandeleur Sound. Silty sand (SM) and sandy silt (ML) are the predominant soil types. No data on strength of the bay-sound soils were available for these 35 borings. Cohesive strengths and densities of the finer grained constituents of bay-sound soils underlying the New Orleans area were available, however, and are summarized in fig. 22. Phleger[80] mapped the bottom sediments of the Breton Island-Pass a Loutre region (29°20'N, 89°10'W), showing their distribution in terms of sand, silt, and clay ratios. He, too, indicates the predominant sediment types to be silty sand and sandy silt. Treadwell[103] sampled the same general area and concluded that sediments consist of 55 to 85 per cent sand sizes, 10 to 40 per cent silt sizes, and 5 to 15 per cent clay sizes.

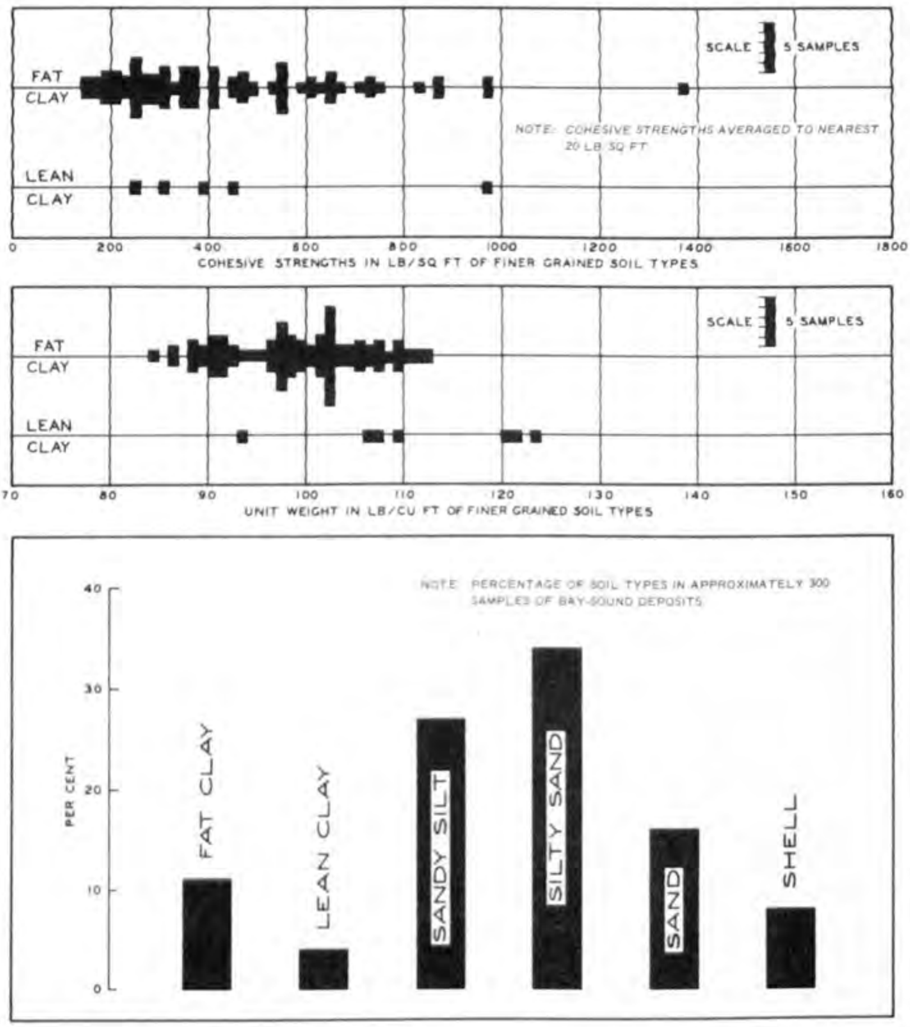



Fig. 22. Selected physical characteristics of bay-sound soils

117. Krumbein[51] studied the bottom sediments of Barataria Bay ($29^{\circ}20'$N, $89^{\circ}55'$W) and divided those within the bay proper into four classes on the basis of grain-size curves. Type I is predominantly sandy, but carries a small amount of silt and clay. This type occurs mainly in the principal channels within the bay where currents are most pronounced ($D_{50}$* = 0.1 mm). Type II borders the main channels of the bay and locally covers large areas of bottom in waters of moderate depth. They contain about 50 per cent sand ($D_{50}$ = 0.08 mm). Type III is predominantly silty, averaging about 25 per cent sand ($D_{50}$ = 0.037 mm). Organic matter is noticeably present in these samples. Type IV includes the finest sediments in the bay ($D_{50}$ = 0.015 mm). This type contains about 15 per cent sand.

* The median grain diameter, see footnote, paragraph 110.

It fringes the low islands in the bay, and in general lies farthest removed from currents. Organic content is high. Krumbein also points out a definite relation between average size and degree of sorting of the sediments. Better sorting is associated with the coarsest sediment; poorer sorting, with the finer sediments.

118. Scruton[92] summarizes some of the depositional irregularities illustrated by cores of bay-sound sediments. "...The most characteristic feature...is the presence of curious pockets, lumps, or irregular lenses which give a mottled appearance to core sections. These lumps or pockets are of coarse material in a fine matrix or fine material in a coarse matrix....Normally they are about one or 1/2 cm in diameter, but they range up to about four cm in diameter. Texture of the lumps and pockets may differ sharply from the matrix or there may be intergradation. Various activities of burrowing organisms apparently produce these features....Irregular variations in the proportions of sand, silt, and clay and in the degree of mixing cause a vaguely mottled or zoned appearance. In some (bay-sound) areas there are also thin irregular beds of sand containing many shell fragments....Development of pockets, lumps, and irregular lenses is poor near shore, but they become prominent seaward as sand content increases."

119. In summary, sediment types within the bay-sound environment are predominantly silty sand and sandy silt. Coarsest sediment and best sorting can be expected in the deepest water where wave and current action are most pronounced. The thickness of the bay-sound deposit averages 10 to 15 ft; the greatest thickness occurs most frequently where depth of water is greatest. The thickness of the deposit, it is believed, is a reflection of subsidence and of the variation between average wave scour and maximum wave scour in reworking bottom sediments.

<u>Reefs</u>

120. The only reef-forming mollusk of importance in southeast Louisiana is the American oyster, <u>Crassostrea virginica.</u> The brackish water clam, <u>Rangia cuneata,</u> which lives on many of the water bottoms does not form reefs. Their remains are mixed singly with lacustrine, bay-sound, and other bottom sediments and although they may locally form sizable proportions of such sediments they seldom reach the concentration of shell material found in reefs.

121. Oysters typically build reefs in nearshore areas where regular influxes of fresh water bring about a mean salinity range between 10 and 30 per cent, and where the mean temperature ranges between 10 and 25 C.[37] Optimum conditions for growth require relatively shallow depths--from 1 to 15 ft of water, but apparently not tidal exposure, and a bottom of mud or sandy mud. Where salinities and temperatures exceed the optimum, the oyster occurs in scattered clusters in the intertidal region rather than in subtidal reefs. The oyster is a sessile or attached bottom dweller. It grows best where there is a fairly firm bottom to which it can adhere. Hence, once a layer of dead shell has been established, successive generations of oysters attach themselves to older oysters or to these shells, and create reef deposits many feet in thickness consisting almost entirely of shell.

122. Hedgpeth[37] describes the typical oyster reef on the Gulf Coast as "...a low mound in cross section, with a high center or 'hogback', which is occupied by dead shells, with live oysters on the sloping shoulders. These reefs occur on muddy bottoms, widely distributed in bays of lower salinities, but more or less restricted to the upper ends of those bays which are subject to the invasion of higher salinites through the passes from the Gulf during periods of low rainfall and decreased run-off. A natural reef is usually oval or spindle-shaped, or is in the form of a narrow bar extending from the shore..., the usual location of such reefs is such that their long axes lie at right angles to the prevailing currents of the bays." Fig. 23 illustrates a typical transverse oyster reef off coastal Louisiana. Only oysters at the far end of the reef and near its edges are alive. Note the small tidal channel separating the reef from the mainland.

123. The manner in which oyster reefs develop, eventually forming bars transverse to the prevailing currents of a bay, was examined by Grave.[29] He suggested that oysters settling on small projections along the shore line grew faster, because of advantageous location with respect to longshore currents, than those elsewhere (fig. 24a). Later generations attach themselves to the shells of oysters already in place, extending the growth of the reefs seaward (fig. 24b). As the upcurrent reef develops seaward it diverts the thread of current, starving the downcurrent reef

Fig. 23. Typical transverse oyster reef developed along southern Louisiana coast. Length of reef approximately 1500 ft.
Photograph by J. R. Van Lopik

(figs. 24c and 24d). As the remaining reef continues to grow the current is diverted around a complexly extending seaward end starving out the portion of the reef attached to the land (fig. 24e). Eventually the major current branches around both ends of the reef and complex current patterns initiated by irregular growth extensions permit sustenance of the entire periphery of the reef (fig. 24f). Finally, the center of the reef is built up out of water to form a shell island. The major trend of the reef-island, however, is still generally at right angles to the shore and to the direction of the alongshore currents. A type that commonly develops in nearshore areas within shallow bays or sounds arranges itself parallel or elongate to the prevailing current direction. Here the reef begins with some bottom irregularity as nucleus and the reef grows in an upcurrent direction.

124. Oyster reefs are also found in tidal channels or in abandoned

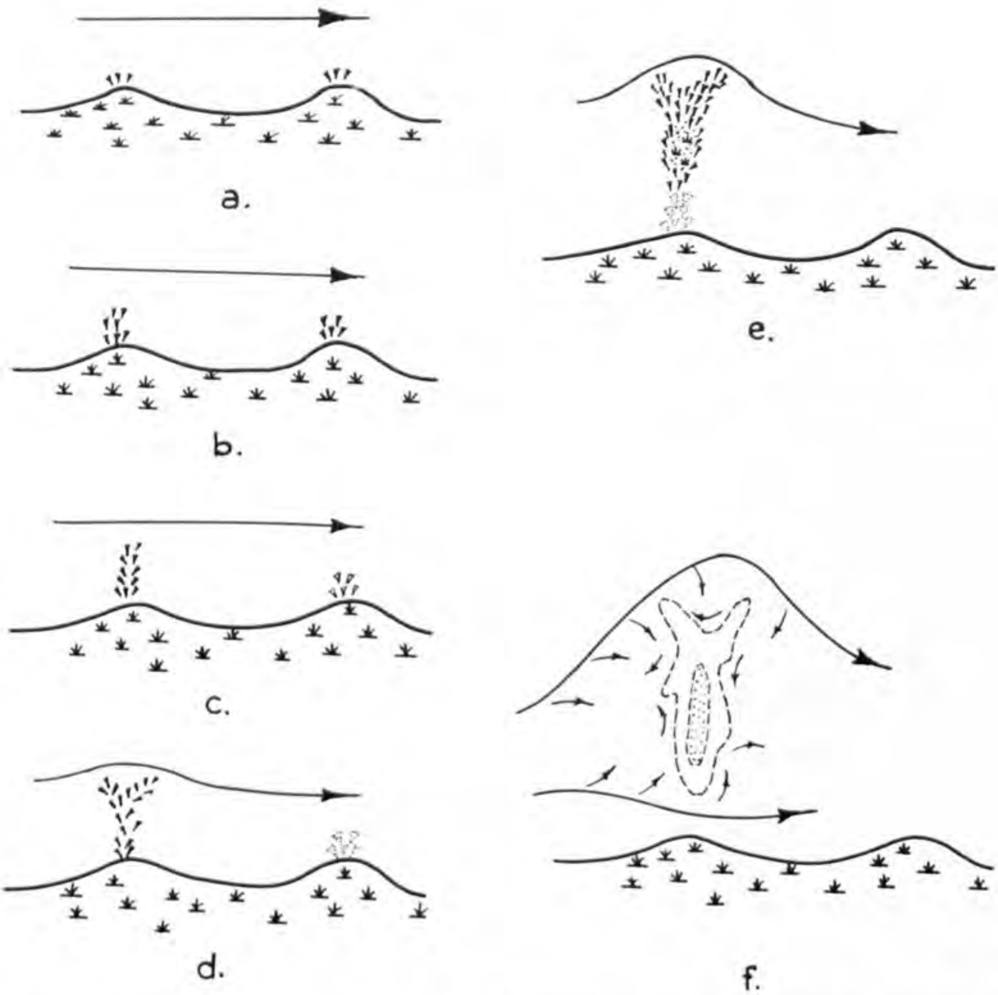



Fig. 24. Hypothetical development of transverse oyster reefs in plan. From references 29 and 37

distributaries now functioning as tidal channels. Treadwell[103] shows several such channels occupied by oyster reefs. These, as the delta subsides or is reworked by marine waters, either become part of the bay-sound sequence or are incorporated in abandoned tidal channel fill.

125. Reefs and reef formation are an integral part of the development of the deltaic plain. Plate 2 shows the locations of the reefs and major shell deposits in the nearshore areas today. It should be emphasized that the scale of mapping and available data permit mapping of these deposits in only the most generalized manner. Plate 8, prepared largely from about 50,000 logs of shot hole borings, delineates areas where significant buried shell deposits were encountered. Data were available for each of the areas shown without the lined overprint. Closely spaced borings,

usually on the order of 2500 ft apart and averaging 100 ft deep, were available for these areas of control. Where a number of closely spaced borings logged a shell bed at essentially the same horizon, the bed is mapped as extensive. Where individual borings encountered a shell bed that adjoining borings failed to penetrate, only the location of the boring is shown. The implication of such data is that the shell beds occur in relatively small isolated patches one of which was penetrated by the individual boring shown. The absence of buried shells in the St. Bernard and the present delta and their occurrence in large numbers in the western portion of the study area are noteworthy.

126. Reef deposits in southern Louisiana range in size from shell clusters tens of feet in length to such massive reefs as the Point au Fer reef (29°20'N, 91°20'W), one-half mile wide and extending across the entire mouth of Atchafalaya Bay some 20 miles in length. Thickness of reef deposits averages between 5 and 10 ft. Buried reef sediments when encountered in scattered bore holes can be distinguished from shell beaches by the greater admixture of silt and clay, poorer sorting, and the unweathered condition of the shell. Treadwell[103] states that the percentage of shell in a typical reef deposit ranges between 45 and 70, the percentage of sand ranges between 15 and 45, the percentage of silt between 5 and 35, and the percentage of clay between 5 and 10.

Beaches

127. From the standpoint of their engineering significance, beaches associated with the deltaic plain of southeast Louisiana fall naturally into two classes, the sand beaches and the shell beaches. Both are beaches in the true sense of the word in that they are gently sloping shores of a body of water washed by waves or tides. The distinctive difference in lithology between the two classes of beaches is due to the availability of sands for the formation of one and of abundant shell material for the formation of the other. Where both sand and shell are available composite types are found, but the configuration of the deltaic plain is such that composite types are rare. Shell beaches are found principally along the landward shores of the bays or sounds where oysters and clams develop in shallow, protected water bottoms consisting principally of organic muds. Sand beaches are found where the land mass or offshore barrier beaches

break the force of the waves developed in the open waters of the gulf, waves capable of reworking sandy deltaic deposits.

128. Sand beaches. Sand beach formation is characteristic of the abandonment of a deltaic system. While the delta is active, small beaches sometimes form where deltaic deposition is light and wave action is particularly vigorous. These, however, are usually of insignificant areal extent. When the delta is abandoned, influx of deltaic sediment ceases and waves begin to rework actively its most seaward or distal ends. Extensive barrier beaches are formed as this sandy material, reworked from the deltaic deposits, is piled by wave action into crescentic shapes which rise slightly above sea level.[111]

129. The Isles Dernieres-Timbalier-Grand Isle and the Breton-Chandeleur Islands arcs form the most important sand beaches of the study area. In addition, small sand spits and beaches are found near the mouths of the Mississippi River. The disposition of the major sand beaches is shown in plate 2 and fig. 25. Fig. 25 also identifies the major beaches from west to east and northeast as the Isles Dernieres, Timbalier Island, Grand Isle, Breton Island, the Chandeleur Islands, and finally Cat and Ship Islands off the southern coast of the state of Mississippi. The beaches range from low, relatively flat, sandy plains only a foot or so above high tide, to massive sandy dune areas, such as Cat Island, that reach heights of 30 ft above sea level. Typical maximum heights are: Grand Isle, 6 ft; Chandeleur Islands, 10 ft; and Cat Island, 30 ft. Widths reach a mile or more but more typically range between 200 and 1300 ft. In profile the beaches typically consist of a relatively steep foreshore backed by a dune area which slopes landward, merging with a marsh or swamp sequence.

130. Fig. 26a shows an idealized cross section of the Chandeleur Islands.[103] Heights of the sand beach vary between 2 and 10 ft and beach width is about a mile. Mangrove swamps greater than a mile in width often occur on the protected inland side. Sand piled on beaches by wave action is reworked by the wind, and gradual rate of landward movement of the chain is attested by the frequent occurrence of exhumed mangrove roots on the seaward side of the beaches.[111]

131. Fig. 26b shows a typical section transverse to Grand Isle. Here the beach sands have bowed down underlying sands, silty clays, and

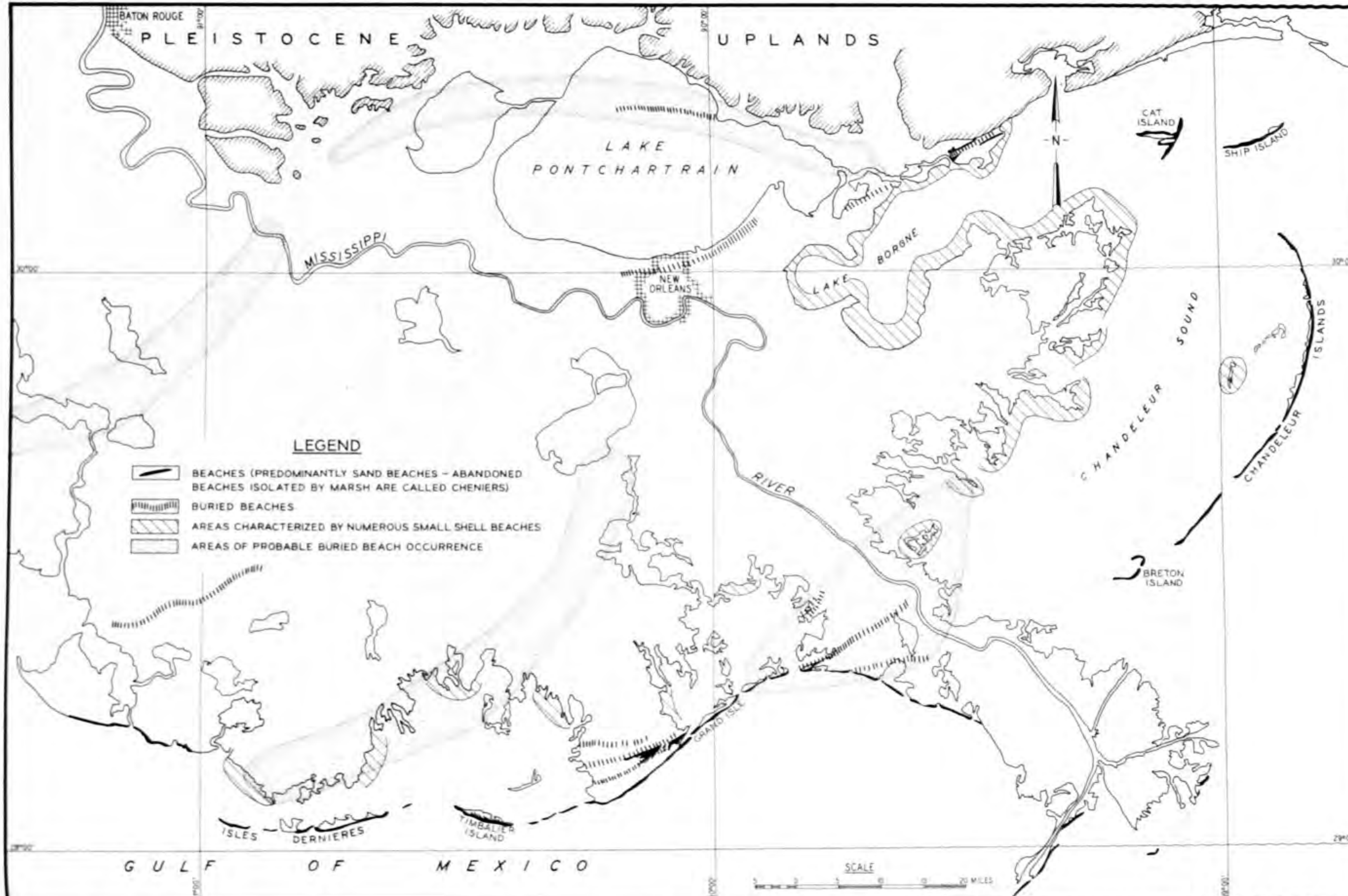



Fig. 25. Distribution of beach deposits

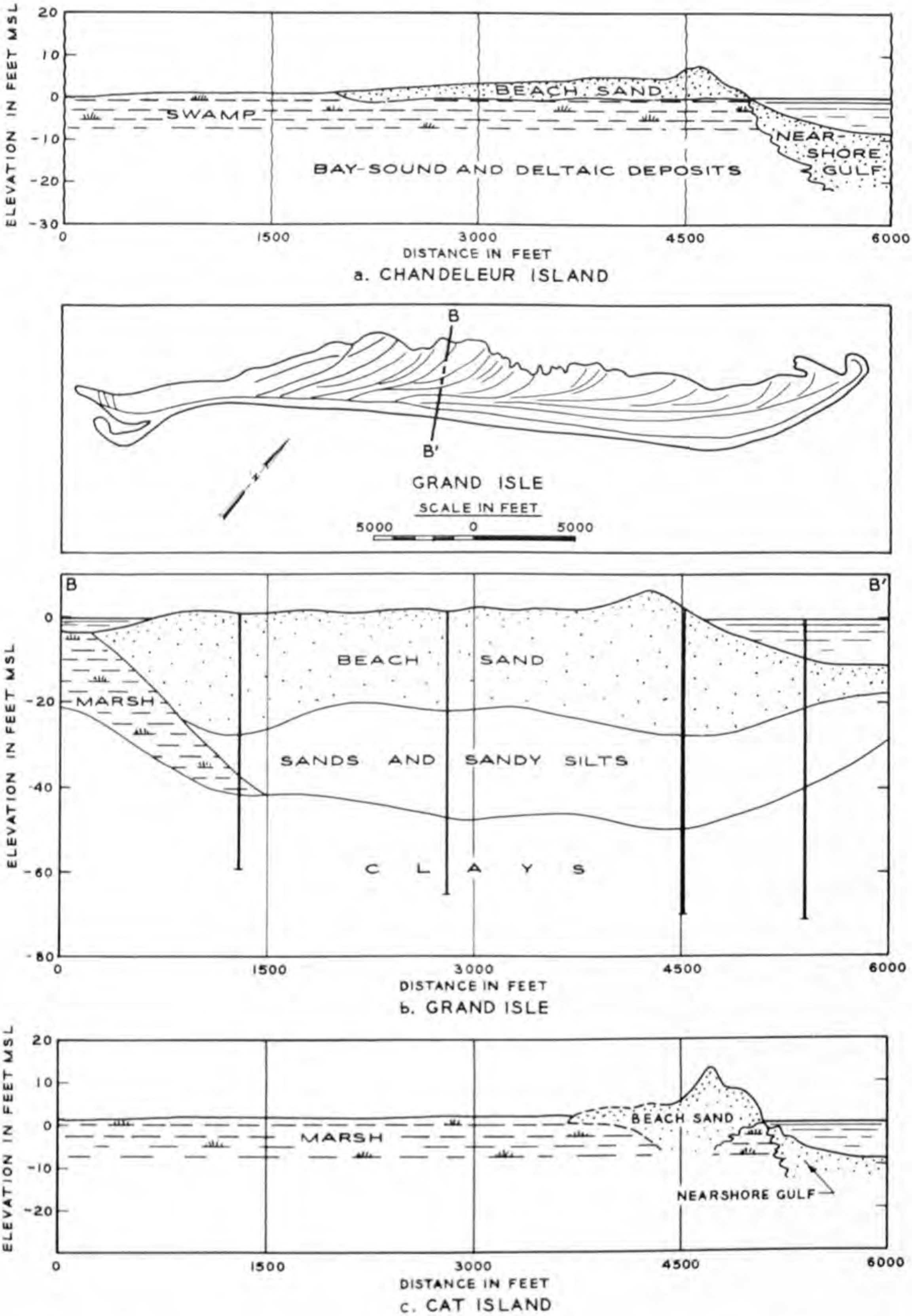



Fig. 26. Sections transverse to typical beaches. From references 26 and 103

clays of the original deltaic sequence so that beach sand thicknesses as great as 35 ft are found. The growth and depositional history of Grand Isle is different from that of the Chandeleurs in that the former, rather than consisting of a single island chain retreating shoreward, consists of a group of closely spaced beach ridges which apparently accreted eastward from a core at its western tip, carried in that direction by a littoral drift operating from west to east.[104] Changes in the historic shore line have principally involved erosion of the western portion of the beach and slight seaward movement of the eastern portion of the beach.

132. Fig. 26c shows a section at right angles to the beach at Cat Island. Note the considerable height of the sand beach which, as mentioned before, reaches 30 ft above gulf level. Here a pair of old beach ridges, once aligned with the Ship Island barrier beach to the east (see fig. 25), forms a central core on which a new and differently trending beach is located. With these old sand ridges as buttresses, dune sands have piled up to an elevation of 30 ft in places at the center and east end of the island. The spits extending north and south of this central core have no such firm support and are only 4 to 5 ft high. As in the Chandeleurs, marsh or swamp deposits are found at fairly shallow depths on the seaward side of the beach, indicating only minor subsidence of the beach into the underlying mangrove swamp deposits.

133. Of considerable importance from the standpoint of the deposits making up the wedge of Recent sediments of the deltaic plain are abandoned and buried beaches. Beaches, now stranded from the sea by an expanse of clay or marsh, are a common occurrence near the present shore line. These features, called cheniers, form groups of narrow ridges which rise slightly above marsh level. Each chenier represents a period when the shore line was locally retreating under wave attack and beaches were constructed from shell and sand debris. The intervening tracts were formed when the influx of fine-grained sediments from the Mississippi deltas was sufficient to build up the gulf floor and to shift the site of wave attack to an offshore position.[26] The major cheniers in the deltaic plain of southeast Louisiana occur just west of Grand Isle ($30^\circ 10'$N, $90^\circ 05'$W); some are also found in Hancock County, Mississippi, just north of Lake Borgne ($30^\circ 10'$N, $89^\circ 30'$W).

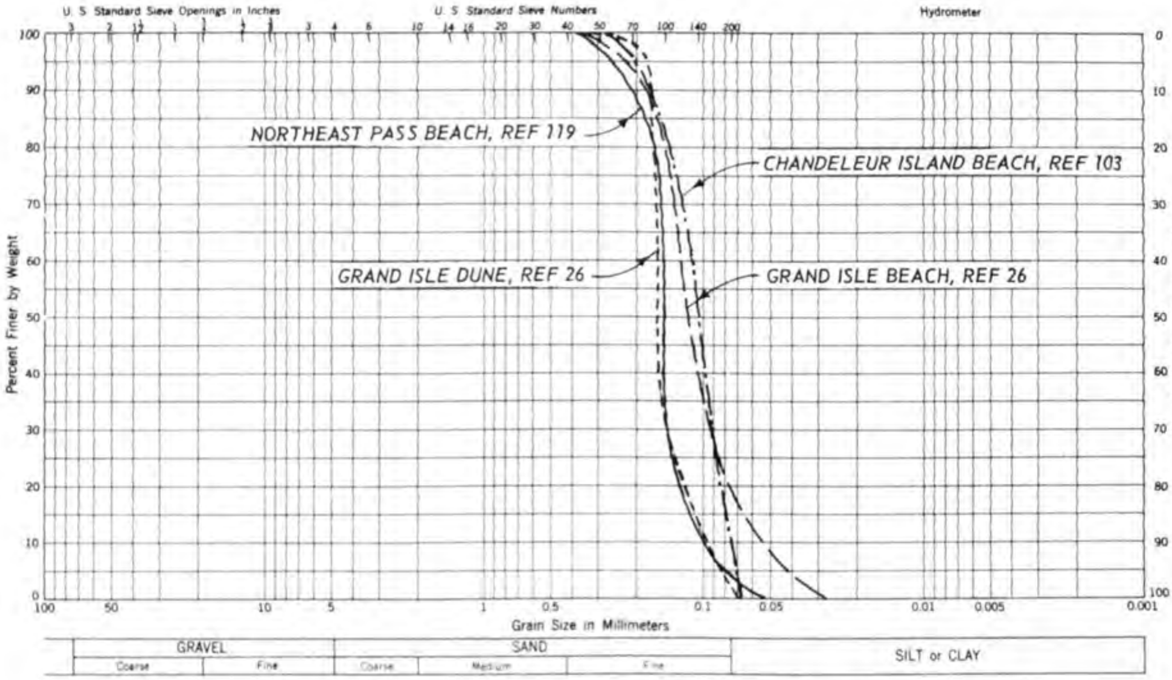
Fig. 27 illustrates the well-defined patterns left by these abandoned beaches in Hancock County, and the growths of live oak from which the features derive their name.

134. Buried beaches, those completely covered by marsh and other deposits, are much more difficult to distinguish and delineate. Although their presence can often be predicted by subtle changes in vegetative or drainage patterns within the marsh, most buried beach trends must be developed from boring data and a knowledge of the most probable zones within which such features occur, e.g., the distal ends of buried deltaic masses, the configuration of the buried Pleistocene surface, etc. Fig. 25 delineates buried beaches fairly well defined by available data, and those areas within the study area where buried beaches probably occur. The location and extent of a massive sand beach forming a significant portion of the subsurface soils in New Orleans are rapidly becoming known because of the large amount of boring data available for that area. Borings shown in plates 12, 14a, and 15 outline the shape and illustrate the soil type associated with this beach deposit. The section in plate 14 defines the limits of a buried beach on the north side of Lake Pontchartrain.

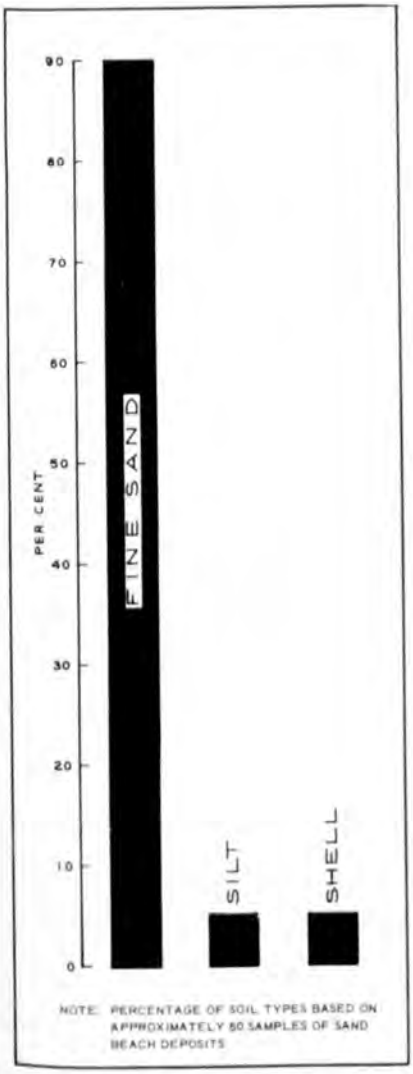
135. Fig. 28 summarizes data on samples taken from sand beaches about the periphery of the deltaic plain of southeast Louisiana. The silt and shell content of these beaches is decidedly subordinate to the sand content. The cumulative grain-size curve emphasizes the well-sorted or poorly graded nature of the beach sands. The tabulation of median grain sizes and sorting coefficients included with the figure has been arranged so that the data presented are from beaches progressing from west to east. Data on one chenier or abandoned beach have been included. See plate 1 for identification of place names listed as beach locations.

136. Shell beaches. Shell accumulations form discontinuous beaches, particularly along the inner margins of bays and sounds and on islands within these water bodies. However, a few flank marshland lake shores and in one case (Point au Fer in the Atchafalaya Bay region), an oyster shell beach borders the open gulf. Waves typically fracture the shell and exposure to sun and water bleaches them to a vivid white. The distribution of the numerous shell beaches in coastal southeast Louisiana is shown in fig. 25.


Fig. 27. Abandoned beaches in southern Hancock County, Miss., marked by northeast-southwest trending bands of trees in the otherwise treeless marsh




GRAIN-SIZE DISTRIBUTION CURVES FOR TYPICAL BEACH SAMPLES




OTHER PHYSICAL DATA:

GRADATION . . . . . . . . . . . . . . . . . . . . . . POOR
ANGLE OF INTERNAL FRICTION . . . . . . . 30–35 DEG
ORGANIC CONTENT . . . . . . . . . . . . . . . VERY LOW

| LOCATION | NO. OF SAMPLES | MEDIAN DIAMETER MM | SORTING COEFFICIENT $S_o$ | SOURCE |
|---|---|---|---|---|
| TIMBALIER | --- | 0.14-0.20 | --- | --- |
| BEACHES FRONTING BAYOU LAFOURCHE | --- | 0.18-0.28 | --- | --- |
| GRAND ISLE | 6 | 0.139 AVG | --- | REF 51 |
| GRAND ISLE | 8 | 0.125-0.180<br>0.170 AVG | --- | REF 104 |
| BASTIAN BAY | --- | 0.08-0.10 | --- | --- |
| SANDY POINT | --- | 0.14-0.18 | --- | --- |
| NORTHEAST PASS | 9 | 0.10-0.20 | --- | REF 119 |
| BRETON ISLAND | 4 | 0.150-0.185<br>0.169 AVG | 1.13-1.21<br>1.16 AVG | REF 103 |
| CHANDELEUR ISLAND | 12 | 0.149-0.175<br>0.159 AVG | 1.09-1.28<br>1.17 AVG | REF 103 |
| CAT ISLAND | 6 | 0.250-0.306<br>0.287 AVG | 1.08-1.17<br>1.12 AVG | REF 103 |
| HANCOCK COUNTY CHENIER | 2 | 0.240-0.425<br>0.332 AVG | 1.07-1.11<br>1.09 AVG | REF 103 |

Fig. 28. Selected physical characteristics of sand beaches

137. Oyster shell beaches vary from about 25 to over 200 ft in width and from 1.5 to 6 ft in height. Lengths may reach a mile or more, but are usually less. They are lens-shaped in cross section. Clam shell beaches are decidedly smaller than their oyster shell counterparts and are restricted, for the most part, to marshland lake and bayou shores. Clam shell beaches seldom exceed 3 ft in height and 50 to 75 ft in width.

138. The typical sequence of deposits associated with this environment consists of 1 to 6 ft of shell, shell fragments, silt, and sand overlying typical marsh sediments. From 25 to 95 per cent of the deposits typically consists of shell. Shell beach deposits, when buried, may be differentiated from reef and bottom shell deposits by (a) the weathered appearance and whiteness of the shell, (b) the fragmental nature of the shell, and (c) lower organic content.

Nearshore gulf

139. Nearshore gulf deposits are the relatively coarse, shelly sediments winnowed from finer grained continental deposits as wave wash and other forms of marine erosion wear back the land surfaces. It is difficult to distinguish between buried nearshore gulf and bay-sound deposits solely on the basis of their lithology. They differ principally in that the former are more sandy than the latter. Environmentally they are distinctive in that nearshore gulf deposits are laid down at the borders of the open ocean, while bay-sound deposits are laid down in relatively quiet waters protected by barrier beaches.[111] Plate 2 shows the general distribution of nearshore gulf deposits seaward of the ring of barrier beaches in southeast Louisiana. The deposits form a continuous blanket seaward of the bays and sounds except where interrupted by active deposition at the mouth of the Mississippi. Here fluvial-marine environments, the prodelta, the interdistributary, and the intradelta, bury nearshore gulf deposits under several hundred feet of sediment.

140. Nearshore gulf deposits in the deltaic plain are associated with a transgressive sea. Where the coast line is advancing at the mouth of a prograding delta such as that of the Mississippi or the Atchafalaya, prodelta muds cover and prevent nearshore gulf formation. When the delta is abandoned the sea advances over the subsiding land surface, waves rework the deltaic materials and permit the coarsest to settle back as a

distinctive stratum. These nearshore gulf sands follow the retreat of the shore line and its associated barrier beaches. The forward edges of the prodelta clays which preceded the outbuilding of the present and each of the past deltas of the Mississippi, buried nearshore gulf sands in their advance. Wedges of these sands marking the seaward zones of overlapping deltaic sequences should, therefore, form a significant portion of the deltaic plain soils.

141. More widespread and continuous are similar deposits that kept pace with rising sea level at the end of Pleistocene and the beginning of Recent times. These are the deposits winnowed by waves from the older Pleistocene deposits as the rising water gradually inundated them. One of the complicating factors in the delineation of these buried basal sandy deposits in borings is their gradation westward in the study area with "strand plain" sands and with coarse fluviatile sands and gravels carried seaward by the ancestral Mississippi River during the rising phase of sea level.

142. Substratum and strand plain. In the upper portions of the Mississippi Alluvial Valley a useful division of the Recent deposits is an upper fine-grained topstratum and a lower coarse-grained substratum consisting of relatively clean sand and gravel.[22] Although the boundary between these two units is transitional, with fine-grained material occurring in lenses below the boundary and limited amounts of coarse-grained material above the boundary, the contact between the two units is one of the most definable and distinctive within the Recent deposits.

143. Substratum sands and gravels become progressively finer grained and deeper in a downvalley direction. In the latitude of Donaldsonville (see plates 10, 11, and 11a) substratum deposits were laid down during the period of waning ice sheets and rising sea level. They represent sediments carried to their present position by early streams with steep gradients which drained the valley long before sea level had reached its present stand. These fluviatile sediments filled the deepest portion of the entrenched valley which trends roughly south-southeast through Houma, Louisiana (see plate 4), and buried the eroded Pleistocene surface beneath a more or less continuous sand, or sand and gravel stratum. Presumably, they also spread out marginally both to the west and eastward into the

study area. Here, it is postulated, the substratum merges laterally with a finer grained sandy deposit of reworked fluviatile deposits, the strand plain facies,[26] and still farther eastward with a sandy deposit reworked by rising marine waters entirely from the underlying Pleistocene, the basal nearshore gulf environment.

144. Control is too limited to permit other than an estimate of the thickness, distribution, and continuity of the basal sandy unit lying above the Pleistocene. The substratum sands and gravels are, of course, continuous and of great thickness. They are differentiated from the strand plain or the nearshore gulf environment because they are normally much coarser and contain little or no shell. Present indications are that the effect of this coarse wave of fluviatile sedimentation is not felt in the study area to any great extent east of a line following Bayou Lafourche. Farther eastward a limited number of borings indicate a fairly continuous thickness of the sand-and-shell strand plain environment above the Pleistocene to a line roughly following the Mississippi River from New Orleans to Head of Passes.

145. Fisk and McFarlan[26] present several generalized sections showing the essential continuity of the strand plain facies in this region. Thickness reaches 50 ft or more to the west where this facies grades into the substratum. The deposit becomes progressively thinner to the east. To the east and northeast, the strand plain grades laterally into the basal nearshore gulf, the deposits of these environments are apparently very similar to each other but distribution of the latter does not appear to be continuous. Some investigators postulate a series of sandy basal deposits during quiescent periods of rising sea level, followed by rapid rises in sea level during which no coarse material of consequence was deposited above the Pleistocene. In such instances prodelta clays rest directly on Pleistocene deposits (see boring 53, plate 17b).

146. Physical characteristics. From an engineering soils standpoint there is no need to distinguish between the strand plain and the basal nearshore gulf environments, and in this report the two are considered synonymous. Both have essentially the same lithology. Substratum deposits, in contrast, are distinctively coarser, contain little or no shell, and are decidedly gravel-bearing.

147. The substratum in the study area consists almost entirely of clean sand and gravel. A number of deep borings made along a line crossing Atchafalaya Basin[107] tested some of the thickest of the substratum deposits. This line of borings extended from Donaldsonville through the northern tip of Lake Verret (29°55'N, 91°10'W) and across the Atchafalaya Basin to Franklin, Louisiana. Substratum deposits vary from 50 to 300 ft in thickness and an estimated 20 per cent consisted of gravel in excess of 10 mm in diameter. Substratum deposits characteristically become coarser with depth.

148. Poorly graded, fine-grained sand forms the bulk of the nearshore gulf deposits. Shell, silt, and clay occur in minor quantities. Borings made in the nearshore gulf areas seaward of the Chandeleur Islands[111] log approximately 60 per cent sand, 20 per cent shell, and some 10 to 20 per cent silt and clay sizes. Scruton[92] in analyzing 31 bottom samples of nearshore gulf deposits found an even higher percentage of sand. He reports 90 per cent sand, 7 per cent silt, and 2 per cent clay. Shells were found to comprise only one per cent of these bottom samples.

## Summary

149. Fig. 29 summarizes and permits comparison of the various ranges of some of the physical measurements characteristic of the depositional types described in Part III. It is emphasized that the classification of Recent environments as presented is predicated on its value in defining or delineating lithologically similar units wherein engineering properties of the soils can be predicted. At the same time the classification has been kept within the framework of accepted geologic terminology.

150. It is also emphasized that a few environments of deposition that may contribute significant proportions of sediment to the Recent soils of the deltaic plain may not be listed in fig. 29. Valid and useful subdivisions of the environments from the standpoint of their associated engineering soils may come to light as more data become available. However, each of the environments chosen for delineation and description is characterized by deposits that form a significant portion of the top 100 to 200 ft of the deltaic plain of southeast Louisiana. Where depositional types

are located at the surface or only partially buried beneath it, airphoto interpretation has proved a very useful tool in determining their limits. Where depositional types are buried, estimates of their areal extent and disposition in plan are dependent on their proper identification in logs of borings and a knowledge of the geologic processes that shaped the area.

| | DEPOSITIONAL TYPES | LITHOLOGY PER CENT (0 25 50 75 100) | PREDOMINANT SOIL TEXTURES[1] | NATURAL WATER CONTENT PER CENT DRY WEIGHT (0 50 100 150 200) | UNIT WEIGHT LB/CU FT (60 80 100 120 140) | SHEAR STRENGTH[2]: COHESIVE STRENGTH LB/SQ FT (0 200 400 600 800) | SHEAR STRENGTH[2]: ANGLE OF INTERNAL FRICTION IN DEGREES | REMARKS |
|---|---|---|---|---|---|---|---|---|
| RECENT ENVIRONMENTS | NATURAL LEVEES | | CH, CL & ML | | | VALUES RANGE TO APPROXIMATELY 2600 CHARACTERISTIC RANGE 800-1200 | ML 20-35 | Disposed in narrow bands flanking the Mississippi River and its abandoned courses and distributaries. Consists of interfingering layers of fat and lean clays and sandy silt along the Mississippi River and its abandoned courses. Natural levee materials along abandoned distributaries usually much finer. Thickness varies from 25 ft near Baton Rouge to 0 at sea level. Thickness along distributaries usually on the order of 5 ft or less. |
| | POINT BAR | | ML, SM & SP | FINE FRACTION ONLY | INSUFFICIENT DATA | INSUFFICIENT DATA | SP 25-35 | Usually found flanking the more prominent bends of the present and abandoned courses to a depth of more than 100 ft. Consists of a bedded topstratum 25 to 75 ft thick of silty sand, sandy silt, and sand coarsening with depth. The substratum consists of essentially clean sand. |
| | PRODELTA CLAYS | | CH | | | | 0 | A homogeneous fat clay in offshore areas and at depth. Contains increasing amounts of lean clay disposed in thin layers near the mouths of active distributaries. Thickness normally varies with depth to Pleistocene. Thicknesses range between 50 and 600 ft. |
| | INTRADELTA | | CH, ML & SM | | INSUFFICIENT DATA | INSUFFICIENT DATA | --- | Relatively coarse portion of subaqueous delta. Intricately interfingered deposits. Disposed in broad wedges about abandoned courses and major distributaries. Thickness of intradelta associated with present Mississippi on order of 200 ft. Thickness of intradelta associated with abandoned courses much less, averaging between 25 to 100 ft. |
| | INTERDISTRIBUTARY | | CH | | | | 0 | Forms clay wedges between major distributaries. Clay sequence interrupted by silty or sandy materials associated with myriad small distributaries. Minor amounts of silts and fine sands typically occur in very thin but distinct layers between clay strata giving deposit a "varved" appearance. Thickness similar to intradelta above. |
| | ABANDONED DISTRIBUTARY | | CH & CL | INSUFFICIENT DATA | INSUFFICIENT DATA | INSUFFICIENT DATA | --- | Forming belts of clayey sediments from a few ft to more than 1,000 ft in width and from less than 10 to more than 50 ft in depth. A wedge of coarser material is normally found at the upstream end, this wedge of material may range from fine sand for the larger distributaries to silty clays for the smaller. |
| | ABANDONED COURSE | | CH & SP | INSUFFICIENT DATA | INSUFFICIENT DATA | INSUFFICIENT DATA | --- | Forming belts of fairly coarse sediment in abandoned Mississippi River courses. Average width 2,500 ft. Depth may be 75 to 150 ft. Lower portion of course filled with sandy material which thickens in an upstream direction. Upper portion filled with silts and clays. |
| | SWAMP | | CH | | | INSUFFICIENT DATA | --- | Tree-covered organic deposits flanking the inner borders of the marsh and subject to fresh-water inundation; also mangrove-choked areas found landward of the barrier beaches and fringing the mainland. Deposits average 3 to 10 ft thick. |
| | MARSH | | PT | VALUES RANGE TO APPROXIMATELY 800 | INSUFFICIENT DATA | VERY LOW | --- | Forms 90 per cent of the land surface in the deltaic plain. Ranges from watery organic oozes to fairly firm organic silts and clays. Maximum thicknesses (10 ft or more) normally associated with areas of greatest subsidence. Average thickness 10 ft. |
| | ABANDONED TIDAL CHANNELS | | PT & CH | INSUFFICIENT DATA | INSUFFICIENT DATA | VERY LOW | --- | Tidal channels found principally in peripheral marsh areas. Average depths on the order of 25 ft. Widths average 200 ft. Material filling abandoned channel varies from peat and highly organic clay in some instances, to fat clay with relatively low organic content in others. |
| | SAND BEACH | | SP | SATURATED | INSUFFICIENT DATA | 0 | 30-35 | Border the open gulf except in areas of active deltaic advance. May be a mile or more in width and more than 10 miles in length. Beach sand may pile as high as 10 ft above gulf level and subside to depths of 10 ft below gulf level. Buried sand beaches reach a thickness of 35 ft in New Orleans area. |
| | SHELL BEACH | | SHELL | SATURATED | INSUFFICIENT DATA | 0 | 30-40 | Border landward shores of protected bays and sounds and marshland lakes. Vary from 25 to 200 ft in width and from 1-1/2 to 6 ft in height. Lengths usually less than a mile. Clam shell beaches usually smaller than oyster shell beaches. |
| | LACUSTRINE | | CH | | | | 0 | Deposits vary in thickness from 2 to 25 ft. Stratification in clayey lacustrine deposits is poorly developed or lacking. |
| | REEF | | SHELL | SATURATED | INSUFFICIENT DATA | 0 | 30-40 | Active reefs found principally in bay-sound areas. Buried reefs a common occurrence within the deltaic plain. Size ranges from shell clusters tens of ft in length to some one-half mile wide and tens of miles in length. Thickness of shell deposit averages between 9 and 10 ft. |
| | BAY-SOUND | | ML & SM | | | | 15-30 | Relatively coarse sediments bottoming bays and sounds. Thickness ranges from 3 to 20 ft and averages 15 ft. Because of the reworking of bottom sediments by burrowing marine organisms soils have a mottled appearance due to the inclusion of lumps or pockets of coarse material in a fine matrix or fine material in a coarse matrix. |
| | NEARSHORE GULF | | SP | SATURATED | INSUFFICIENT DATA | 0 | 25-35 | Found at the borders of the open ocean seaward of the sand or barrier beaches. Thickness appears to increase with distance from shore--maximum thickness believed to be on order of 25 ft. Discontinuous blanket of this material occurs directly above Pleistocene. |
| | SUBSTRATUM | | SP | SATURATED | INSUFFICIENT DATA | 0 | 30-40 | Massive sand and gravel deposits filling entrenched valley and grading laterally into near-shore gulf deposits. Material becomes coarser with depth. Maximum thickness on the order of 300 ft in deepest portion of entrenched valley. |
| PRE-RECENT | PLEISTOCENE | | CH & CL | | | VALUES RANGE TO APPROXIMATELY 3500 CHARACTERISTIC RANGE 900-1700 | 0 | Ancient former deltaic plain of Mississippi River. Consists of environments of deposition and associated lithologies similar to those found in recent deltaic plain. Depth to this ancient, eroded surface increases in a southerly and westerly direction in southeastern Louisiana. |

LEGEND

GRAVEL (>2.0 MM) — SAND (2.0-0.05 MM) — SILT (0.05-0.005 MM)

CLAY (<0.005 MM) — ORGANIC MATERIAL — SHELL

TYPICAL RANGE OF VALUES INDICATED BY LENGTH OF BAR. BAR WIDTH INDICATES RELATIVE DISTRIBUTION OF VALUES.

(1) SYMBOLS BASED ON UNIFIED SOIL CLASSIFICATION SYSTEM

(2) SHEARING STRENGTHS OF CLAYS BASED ON UNCONFINED COMPRESSION TESTS

Fig. 29. Typical properties of depositional types within the deltaic plain

## PART V: SUBSIDENCE OR APPARENT SEA LEVEL RISE IN COASTAL LOUISIANA

### Introduction

151. Parts II, III, and IV have repeatedly introduced the factor of subsidence in tracing the development of each environment of deposition. As has been pointed out in Part IV, marshes and their associated deposits build upward as the lowlands bordering the gulf subside. If it were not for the continuing downward movement of the deltaic plain, it is estimated that coastal Louisiana would extend a considerably greater distance seaward and encompass an additional 8500 sq miles. Marine erosion--the wearing back of the land borders by wave attack--is an important factor in shore-line retreat, but in the deltaic plain land loss resulting from this factor is relatively minor when compared with the area lost through submergence of land beneath bay and sound waters as a result of subsidence. It is also true that without subsidence marine erosion would be less effective.

152. In the following paragraphs an attempt will be made (a) to isolate the component parts of the complex phenomenon of subsidence in the deltaic plain, (b) to ascribe a reasonably accurate quantitative measurement to each component part and to the factor as a whole, and (c) to speculate on the effect of subsidence on present and future engineering programs in the area.

153. Evidence of changes in the relative elevation of land and sea during the Recent Epoch (i.e., last 15,000 to 17,000 years) is common throughout coastal Louisiana. Regions of obvious deltaic origin lie considerable distances offshore submerged beneath two or three fathoms of water. Natural levee ridges, their crests now lowered below marsh level, abound. These and numerous other data indicate that subsidence--the relative lowering of the land surface with respect to sea level--has played and continues to play an important role in southern Louisiana.

154. Subsidence is the result of several concomitantly operative processes and it would be fallacious to ascribe an apparent sea level rise solely to a lowering of the land surface or, on the other hand, to a rise in sea level. In the Gulf Coast area the following factors must be

considered in evaluating apparent vertical movements in land and sea:

A. True or actual sea level rise

B. Basement sinking caused by sediment load and/or subcrustal flow

C. Consolidation* of sediments of the Gulf Coast geosyncline

1. Pleistocene and pre-Pleistocene sediments

2. Recent sediments

D. Local consolidation

1. Consolidation caused by weight of minor landforms

2. Consolidation caused by weight of manmade structures

E. Tectonic activity

Thus, if we designate total subsidence or apparent sea level rise as "S," an equation may be set up wherein $S = A + B + C_1 + C_2 + D_1 + D_2 \pm E$ . Fig. 30 presents a generalized cross section of the Gulf Coast geosyncline and depicts the above-mentioned components of an apparent sea level rise. Note that the Recent, although as much as 1000 ft thick, forms only a relatively thin deposit capping 40,000 ft of Tertiary and Pleistocene sediments. Note also that the Recent reaches its maximum thickness in nearshore areas. North of Houma its thickness (usually less than 300 ft) can be shown as a line at the vertical scale utilized in the figure.

## Apparent Sea Level Rise or Total Subsidence (S)

155. One measure of apparent sea level rise or total subsidence is recorded in tide gage readings which extend over considerable periods of time. Such tide gage data are not available for stations along the Louisiana coast; however, Marmer[62] provides figures for Key West, Cedar Keys, Pensacola, and Galveston. At all four of these Gulf Coast stations an apparent sea level rise of varying magnitude has been recorded during the last 30 to 40 years. Concerning Galveston, Marmer states, "...The results are especially interesting since a continuous series of 40 years is

* Although consolidation to the geologist refers to any or all of the processes whereby loose, soft, or liquid earth material become firm and coherent, in this report it is used in the soil mechanics sense, i.e., the adjustment of a soil in response to increased load and involves the squeezing of water from the pores and decrease in void ratio. This latter process is called compaction by the geologist.

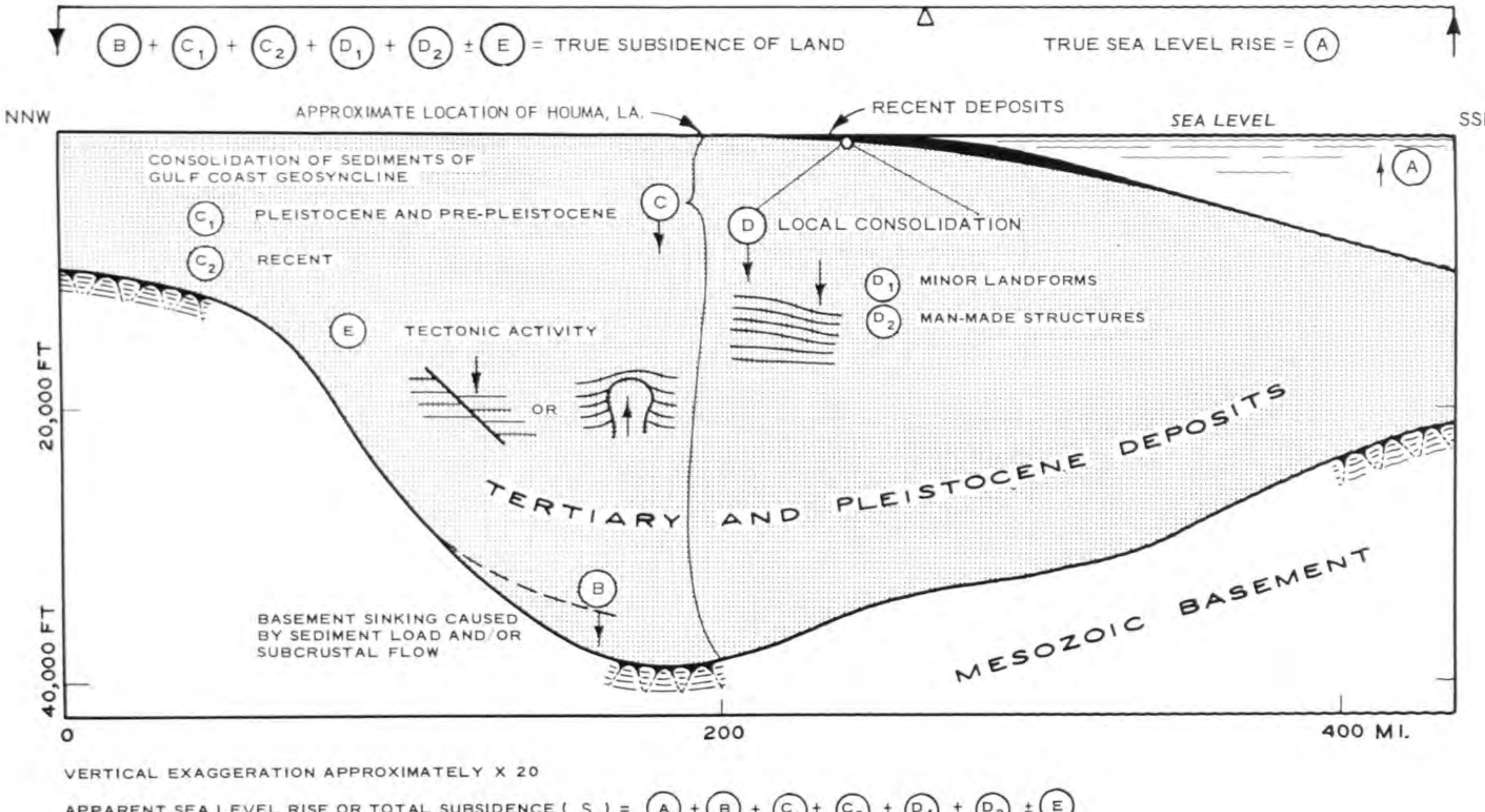



Fig. 30. Generalized cross section of Gulf Coast geosyncline depicting components of apparent sea level rise

available. During this time sea level has changed by almost exactly one foot, but the results clearly indicate a change in the rate of rise between 1937 and 1938. From 1909 to 1937 the rise was at the rate of about .015 foot per year, while since that year the rise is at the rate of about .05 foot per year or more than 3 times the previous rate." At Key West there was little change until 1930, but a rise since that time of .02 foot per year. The Cedar Keys data exhibit a definite rise since 1939. At Pensacola an acceleration in the rate of rise occurred in 1940. Although the high Galveston values are probably the result of associated tectonic movement, the important point is that the entire Gulf Coast is evidently experiencing a relative or apparent rise of sea level that has been accelerated during the last 15 to 20 years.

156. Table 3 provides several figures on the rate of total subsidence or apparent sea level rise in southeastern Louisiana. The validity of the basic data, interpretational methods, the length of time considered, as well as the component factors that determine apparent sea level rise, are reflected in these estimates. The figures will be mentioned in subsequent paragraphs and, although but rough estimates, they indicate that subsidence in southeastern Louisiana is a significant process that should be considered--particularly in long-range development schemes.

## True or Actual Sea Level Rise (A)

157. Theoretically true sea level rise would be recorded by tide gage readings along an absolutely stable coast. As the location or even the existence of such a coast is in doubt, it appears that the best estimates of this factor are the determinations based on volume of glacier melting. Thorarinsson[99] states, "...The ice-thinning in the last few decades of the world's glacier districts, exclusive of the whole Antarctic and the accumulation area of Greenland ice, has thus--certeris paribus--resulted in the ocean level's being raised eustatically about 0.05 cm (.0016 ft.) per annum." In view of the facts that glacier melting is now proceeding at an accelerated pace[63] and all glacier districts were not considered in Thorarinsson's figures, the present rate of rise can conservatively be estimated as 0.32 ft per century.

## Table 3

### ESTIMATED SUBSIDENCE RATES IN SOUTHEASTERN LOUISIANA

| Area | Nature of Basic Data | Rate of Total Subsidence As Presented | ft/Century | During the Period | Source |
|---|---|---|---|---|---|
| Louisiana Coast | Calculation based on comparison of subsidence rates and volume of sediment in the Netherlands and New Jersey. | 1 ft per century | 1 | ? | Ref 88 and 65 |
| The Jump – Lower Delta | Subsidence rate of telegraph cable across The Jump. | 2 ft per yr | 17 | 1853–1877 | Ref 88 |
| Ports Eads – Lower Delta | Subsidence of tide gage at Port Eads. | 0.059 ft per yr | 5.9 | 17 yr | Ref 88 and 53 |
| Ports Eads – Lower Delta | Subsidence of tide gage at Port Eads. | 0.1 ft per yr | 10 | ? | Ref 88 and 93 |
| Ports Eads – Lower Delta | Subsidence of tide gage at Port Eads. | 0.3 in. per yr | 2.5 | ? | Ref 88, 15, 55 |
| Burrwood | ? | 0.9 in. per yr | 7.5 | ? | Ref 88, 15, 55 |
| Head of Passes | ? | 0.2 in. per yr | 1.7 | ? | Ref 88, 15, 55 |
| East Bay – Lower Delta | Subsidence of East Bay bottom between the 1869 and 1917 hydrographic surveys. | 0.16 ft per yr | 16 | 1869–1917 | Ref 88 and 15 |
| Balize – Lower Delta | Subsidence of the Spanish Magazine at Balize. | 0.05 ft per yr | 5 | 200 yr | Ref 88 and 12 |
| Balize | Subsidence of shell streets in Balize and vault in nearby cemetery. | 0.08 ft per yr | 8 | 50–75 yr | Ref 88 |
| St. Bernard | Subsidence of outer fringes of St. Bernard delta. | 0.01 ft per yr | 1 | 900–1200 yr | Ref 88 |
| Burrwood – Lower Delta | ? | 0.09 to 0.12 ft per yr | 9 to 12 | ? | Ref 88 |
| Head of Passes | ? | 20 in. per century | 1.7 | ? | Ref 88 |
| Balize | Subsidence of tombstone in Balize cemetery. | 0.04 ft per yr | 4 | 1858–1952 | Ref 119 |
| Cubits Gap | Subsidence of Bay Rondo bottom between 1885 and 1952. | 0.15 ft per yr | 15 | 1885–1952 | Ref 119 |
| St. Bernard | Subsidence of St. Bernard delta. | 0.02 ft per yr | 2 | 1000–1200 yr | Ref 111 |
| Burrwood | Thickness of bar sands in Burrwood boring. | -- | 20 | 500 yr | Ref 25 |
| New Orleans | Carbon-14, see Plates 9 and 9a, Sample No. 10. | -- | 0.85–1.0 | 1200 ± 100 | * |
| East of Napoleonville | Carbon-14, see Plates 9 and 9a, Sample No. 11. | -- | 0.56–0.86 | 800 ± 100 | * |
| East of Houma | Carbon-14, see Plates 9 and 9a, Sample No. 12. | -- | 0.35–0.45 | 750 ± 100 | * |
| South of Houma | Carbon-14, see Plates 9 and 9a, Sample No. 14. | -- | 0.88–2.2 | 700 ± 100 | * |
| SW of Baton Rouge | Carbon-14, see Plates 9 and 9a, Sample No. 16. | -- | 0.30–0.35 | 1250 ± 100 | * |
| New Orleans | Carbon-14, see Plates 9 and 9a, Sample No. 20. | -- | 0.44–0.47 | 2650 ± 110 | * |
| W of New Orleans | Carbon-14, see Plates 9 and 9a, Sample No. 21. | -- | 0.13–0.14 | 2320 ± 110 | * |
| Near English Turn | Carbon-14, see Plates 9 and 9a, Sample No. 55. | -- | 0.82–1.3 | 1400 ± 350 | Ref 27 |
| St. Bernard | Carbon-14, see Plates 9 and 9a, Sample No. 67. | -- | 0.25–0.36 | 1830 ± 100 | ** |
| St. Bernard | Carbon-14, see Plates 9 and 9a, Sample No. 72. | -- | 0.4–0.5 | 900 ± 100 | ** |

* Brannon, *et al*, "Humble Oil Company Radiocarbon Dates II," *Science*, vol 125, No. 3254, May 1957.

** ———, "Humble Oil Company Radiocarbon Dates I," *Science*, vol 125, No. 3239, January 1957.

## Sinking of Basement Caused by Sediment Load and/or Subcrustal Flow (B)

158. Since the beginning of the Tertiary Period (approximately 60 million years ago) a thickness of some 40,000 ft of shallow water sediments has been deposited in the Louisiana coastal region. This great mass of sediment accumulated here through downwarp resulting from the ever-increasing depositional load and/or the creation--through the process of subcrustal flow--of a gradually subsiding trough. Although periods of rapid deltaic sedimentation alternated with periods of marine transgression during this time, an average rate of downwarp during the last 60 million years is approximately 0.07 ft per century. It should be emphasized that this figure is an average, and downwarp of this basement surface should be greater during times of maximum deltaic deposition, such as has characterized the Recent Epoch.

## Consolidation of Sediments of the Gulf Coast Geosyncline (C)

### Consolidation of Pleistocene and pre-Pleistocene sediments ($C_1$)

159. The effect of local depression-consolidation of the Pleistocene and pre-Pleistocene deposits of the Gulf Coast geosyncline accounts for a considerable percentage of subsidence in coastal Louisiana. Except for relatively brief intervals of marine erosion, deposition has been continuous and the sediments constantly adjust themselves to the newly acquired loads. The upper surface of this 40,000-ft wedge of sediment is the Pleistocene, and the rate at which this eroded surface has been bowed down beneath the Recent deposits is fairly well documented.

160. Some of the most rapid consolidation of this thick wedge of sediment is believed to have occurred in its uppermost portions during the lowering of sea level in Pleistocene time. At such times, when sea level dropped approximately 400 ft, the Pleistocene and Tertiary sediments forming the land areas were dewatered or drained thus resulting in consolidation in excess of the normal or average rate. A second cause for subsidence of the Pleistocene surface, of course, is the great weight of Recent

materials deposited on this surface during and subsequent to sea-level rise. It is estimated[27] that a total of 6000 cu miles of sediment reaching a maximum thickness of 1000 ft have been deposited on the Pleistocene surface since the beginning of the Recent Epoch. Of this amount, 2300 cu miles underlie the modern deltaic plain and the continental shelf. As this sediment load accumulated, adjustments occurred in the underlying Pleistocene resulting in the downwarp of its weathered, oxidized surface.

161. Fisk and McFarlan[27] have reconstructed the Pleistocene surface prior to erosion based on the configuration of the relatively uneroded areas and the maximum heights of interfluves in the eroded regions. Contours on this surface show the Pleistocene to be bowed downward in a huge east-west trending, scoop-shaped depression--extending from Vermilion Parish on the west to the Mississippi-Alabama line on the east, and southward from a line trending northeast-southwest through Donaldsonville. Downwarp along a line extending southward from Donaldsonville through Houma increases from 0 to 350 ft near the present shore line, to 500 ft at the edge of the Pleistocene (Prairie) continental shelf. Consequently, within the southeastern Louisiana study area, downwarp of the Pleistocene surface increases both toward the south and west from 0 at the Prairie outcrop in the north to a maximum of 350 ft. Assuming that this downwarp occurred during a period of approximately 45,000 years, i.e., from the beginning of the last major lowering of sea level or glacial stage, the rate of subsidence for the Pleistocene surface in southeastern Louisiana ranges from 0 to 0.78 ft per century--the highest rates occurring in the south and west. An average rate of 0.39 ft per century is considered to be realistic for southeastern Louisiana.

Consolidation of Recent sediments ($C_2$)

162. Subsidence of Recent sediments due to compaction or consolidation is most pronounced in areas of active deposition, i.e., the deltas. During the time a delta is active the deposits build "down" rather than "up." This method of growth is obvious from the fact that the same approximate surface elevation is maintained while considerable thicknesses of sediment accumulate--the thicknesses in excess of the original depth of the gulf water into which the sediments were deposited. Upon abandonment of a

delta, however, deposition ceases and subsidence of the deltaic mass continues at a gradually decreasing rate. In other words, other factors being equal, a recently abandoned delta region will subside more rapidly than a similar area abandoned three or four hundred years previously.

163. This fact is reflected in the rate of shore-line retreat at the deltaic periphery. Shore-line retreat is, in general, most rapid in areas of recently abandoned deltas and progressively slower along increasingly older deltaic coasts.[72] Time-consolidation curves[98] based, in addition to other factors, on the submerged weight of sediment deposited per unit of time and unit of area--or the rate of sedimentation--indicate that the rate of sedimentation of prodelta clays is such that consolidation takes place almost coincident with deposition. The rate of sedimentation of the intradelta and interdistributary materials, however, is so great that more than 3000 years may be necessary before these rapidly deposited sediments are normally consolidated. It should be mentioned here that much more rapid rates of consolidation can be expected in the coarser intradelta materials, interdistributary clays consolidating much more slowly. Data on the older Mississippi River deltas are too sparse to be conclusive, but the thick, rapidly deposited interdistributary clays of the present delta are consistently underconsolidated (see fig. 13). A trend toward underconsolidation in comparable sediments is apparent but not nearly so pronounced in the abandoned St. Bernard Delta. Whether consolidation has ceased in the most ancient of the abandoned deltas, such as Salé-Cypremort, is problematic. The point is, that a great proportion of the subsidence in the deltaic plain is undoubtedly due to consolidation of Recent materials. The most ancient of these materials are probably normally consolidated, and subsidence due to further consolidation should be minor. Progressively younger deltas should exhibit progressively more subsidence due to consolidation. This explains, to some extent, the high rates of subsidence within the present delta shown in table 3. It does not explain, even after allowances have been made for variation in consolidation rates resulting from soil type differences, the very erratic rates noted for some of the abandoned deltas, and it can only be assumed that some estimates listed in the table are in error or that subsidence factors other than consolidation of Recent deposits are responsible for these anomalies.

164. An important consideration that should be borne in mind is the volumetric and spatial relations among the wedges of sediment forming the Gulf Coast geosyncline: the wedges of sediment left by the present and each abandoned delta in the much more extensive mass of Recent deposits, and the position of the relatively small mass of Recent deposits, in turn, within the great 40,000-ft thickness of the Gulf Coast geosyncline (see fig. 30). Active sedimentation is confined principally to a small delta lobe, and although this deposition affects all underlying deposits it does so to a lesser degree than the general downwarp of the Pleistocene surface caused by the entire mass of Recent sediments. Once Recent sediments become normally consolidated ($C_2$), further regional subsidence can be more logically attributed to the factors A, B, $C_1$, and E.

## Local Consolidation (D)

### Consolidation caused by weight of minor landforms ($D_1$)

165. Minor landforms within the delta complex often exert a downward force which may be differentiated from the more regional deltaic lowering of the surface. Local consolidation is similar in most respects to the much larger scale subsidence phenomena associated with consolidation of the Recent sediments ($C_2$). However, because it is very local in its effects, it must be considered separately. Where local consolidation occurs, the surface is depressed in amounts significantly in excess of that affecting the Recent deposits as a whole.

166. In fig. 31 the vertical movements labeled C on the levee and chenier cross sections can be assigned to local consolidation caused by the weight of the overlying landform. The distances labeled S are the result of concomitantly operative processes of (A) actual sea level rise, (B) basement sinking, (C) consolidation of sediments of the Gulf Coast geosyncline, and (E) tectonic activity. The relative values assigned to the distances C and S are for illustrative purposes only. Such values, and their relative magnitude, vary greatly depending on the area where the minor landform occurs.

167. It should also be pointed out that there is a tendency for

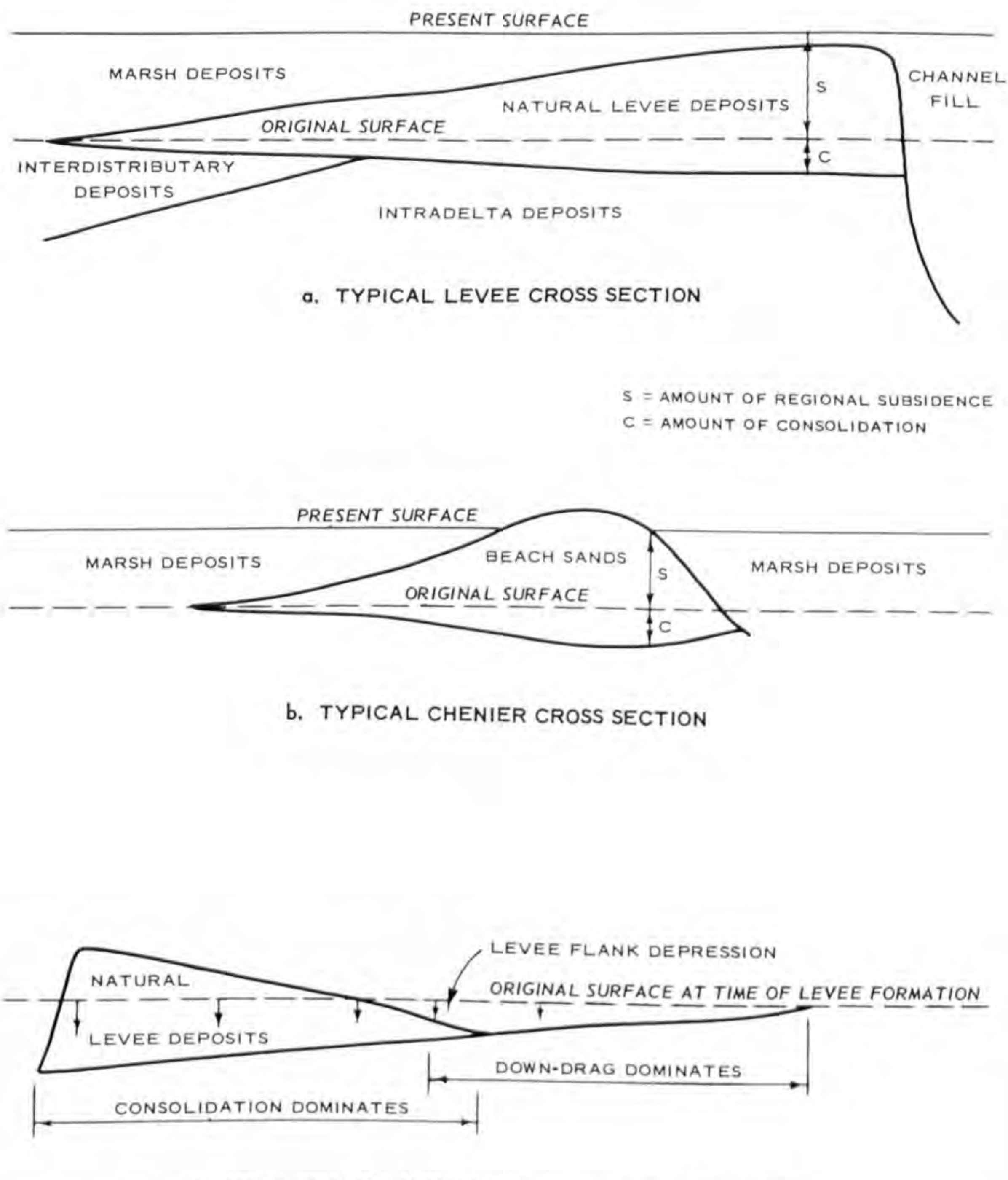



Fig. 31. Subsidence phenomena associated with weight of minor landforms

various landforms and manmade structures (see next paragraph) to drag down adjacent areas. Here downwarping is effective not only directly beneath these features but to considerable distances to their flanks. Consolidation along the flanks of a natural or artificial load has been termed "down-drag."[88] One of the most commonly occurring phenomena of this type results in the levee-flank depressions often associated with natural levees (fig. 31c).

Consolidation caused by weight of manmade structures ($D_2$)

168. Unless structures are constructed on large natural levees or on piles bottomed in firm materials they sink rapidly into deposits of low bearing capacity. Embankments and channel-flanking spoil banks, when underlain by marsh, often subside to half their height almost immediately and continue slow subsidence for years after their completion. Soils engineers can predict with a great deal of accuracy the amount of subsidence due to consolidation that can be expected beneath a given structure. Less amenable to prediction is the long-range, slowly developing subsidence caused by the consolidation of sediments beneath the larger towns and cities of the deltaic plain.

## Tectonic Activity (E)

169. In the Gulf Coast, where most faults are down-dropped gulfward, movement in the underlying strata often accentuates the apparent sea level rise or total subsidence. Abrupt narrowing of some natural levee ridges in south Louisiana and sharp changes in the course of the Mississippi River south of New Orleans suggest that faulting has affected the present deltaic surface. Undoubtedly faulting occurs in the underlying strata; however, owing to the relatively unconsolidated nature of the Recent deposits, such movement usually finds little obvious expression in the surface of the deltaic plain. Most movement probably occurs in spasms, and average rates of movement, which would allow a prediction of the tectonic portion of total subsidence, would be very difficult to establish. Furthermore, the collection of detailed information concerning the location and possible movement along faults within the Gulf Coast geosyncline is much too formidable a

task to be attempted at the present time. Were these data collected, however, it might be possible to roughly estimate the portion of total subsidence due to faulting. In the present study, although tectonic activity is recognized as an important and operationally distinct process, its effects are inseparably incorporated in the regional subsidence rates estimated for factors A, B, and C.

170. Recurring movement of salt domes gives rise to uplift which locally negates or detracts from the apparent sea level rise. Many of these columnar masses of rock salt have intruded to within a few hundred feet of the present surface; however, estimates of rate of uplift vary greatly in relatively small areas and, very possibly, within short time spans. On a very local basis, the rise of mudlumps (see paragraphs 68-70) causes uplift within the present active delta region of southeastern Louisiana.

## Summary and Applications

171. It is apparent from the preceding discussion that only three of the component factors, true sea level rise (A), basement sinking (B), and consolidation of the Pleistocene and pre-Pleistocene sediments ($C_1$), are sufficiently broad in aspect to permit general application to all of southeast Louisiana. Although the subsidence rates dictated by these factors vary considerably with geologic time, thus making average rates less indicative, it is felt that minimum values have been established. Therefore, the sum of the values for true sea level rise (0.32 ft per century), basement sinking (0.07 ft per century), and consolidation of Pleistocene and pre-Pleistocene sediments (0.39 ft per century) should provide an average regional subsidence rate (0.78 ft per century) for southeastern Louisiana at the present time. As a distinct component rate cannot be presently assigned to regional tectonic activity (E), the 0.78 figure includes the effect of this factor. In addition, it should be borne in mind that this value is a regional estimate and local deviations resulting from compaction of Recent sediments ($C_2$), consolidation caused by weight of minor land forms ($D_1$), consolidation caused by weight of manmade structures ($D_2$), and local faulting or uplift (E), as well as normal deviations from the average should be expected.

172. In view of the above-mentioned facts, it is interesting to re-examine the total subsidence rates presented in table 3. If all average rates presented were greater than the 0.78 ft per century figure the differences could be ascribed primarily to the position of the sample on which the rates were based with respect to the maximum downwarping of the Pleistocene surface ($C_1$), to variations in the consolidation of Recent sediments ($C_2$), or to more local considerations. However, many estimated rates are less than 0.78 ft per century. Such anomalies must be explained by local uplift (E), by errors in interpretation of data utilized in formulating the estimates, or by errors in isolating and establishing rates for the various components of total subsidence. It is felt that the latter may indeed be true and that only through collection of additional information and further intensive study of all data can a more accurate and quantitative attempt be made at the measurement of subsidence in southeastern Louisiana. The attempt made herein should not be considered more than a necessary preliminary endeavor.

173. For the present several broad statements concerning subsidence in this region can be made: (1) subsidence is greatest--on the order of five or more feet per century--in the present Mississippi River Delta; (2) subsidence on the order of one to two feet per century is a realistic figure at the present shore line throughout the remainder of the study area; (3) subsidence decreases with distance inland and approaches zero at the surface Recent-Pleistocene contact.

174. Subsidence caused by engineering structures ($D_2$) can be accurately calculated. On the other hand the effect of long-range regional subsidence on these structures can only be based on data such as those presented here. Long-range planning for control of the river depending on precise elevations, municipal developments and their future protection from floods, the effect of long-range confinement of the Mississippi River between artificial levees and the gradual inundation of the deltaic plain as a result of subsidence, are but a few of the items that are affected by the omnipresent factor of subsidence. For some long-range considerations, subsidence of the order of magnitude prevalent in southeastern Louisiana may be negligible; for others it may be a key factor that might easily be overlooked. In any event, there can be little doubt that as the rapid

industrial and commercial development of the deltaic area continues, engineers will become more and more cognizant of the factor of subsidence and its effect on engineering projects and programs.

# PART VI: CONCLUSIONS AND RECOMMENDATIONS

## Conclusions

175. The engineering soil types composing the sediment underlying the deltaic plain of southeast Louisiana can be readily and advantageously associated with the environment within which each was deposited. Delineation of environments of deposition permits reasonably accurate estimates of subsurface soil types, typical ranges of many of their physical properties, and their distribution in plan and profile. Conversely, physical properties of soils encountered in bore holes are sufficiently diagnostic so that environments within which they were deposited can usually be determined. This permits reconstruction of buried environments based on fewer and more carefully located borings.

176. Subsidence, an important factor in deltaic plain morphology, varies from more than 5 ft per century within the present Mississippi River Delta to less than 2 ft per century at the shore line of the remainder of southeast Louisiana. It occurs at a progressively diminishing rate inland from the shore line.

## Recommendations

177. It is recommended that:

a. Additional data be collected in order to develop a comprehensive chronology for the sequence of geologic events in the deltaic plain. This involves: (1) the continued collection of samples for Carbon-14 dating, and (2) the assessment of the resulting data in terms of geologic chronology.

b. Collection and analysis of data on the processes of formation, lithology, and engineering properties of the environments of deposition in the deltaic plain, be continued. The following environments, in particular, need further study: the marsh, tidal channels, the reefs, intradelta and interdistributary, and the abandoned courses and distributaries.

c. Criteria be developed for possible airphoto identification of the various environments both at the surface and when buried at shallow depths.

d. More definitive criteria be developed for determining the magnitude and rate of subsidence in the deltaic plain.

e. Liaison be continued with the various organizations engaged in deltaic plain and shallow offshore sedimentation research.

# SELECTED BIBLIOGRAPHY

178. The following list of references encompasses a small portion of the voluminous literature concerning southeastern Louisiana and/or the processes typical of the area. As a good annotated bibliography of southeastern Louisiana was prepared by R. J. Russell and C. F. Dohm in 1936,[88] it is attempted herein to extend this bibliographic coverage to the present time while avoiding, as much as possible, duplication of items published prior to 1936. Several items published prior to 1936 of special significance in the present study have been added. Other fairly extensive bibliographies are found in references 37, 66, 92, 102, 103, 113, 119, 126, 129, and 132. In addition, the sedimentation section of the series of annotated bibliographies on tidal hydraulics[13] contains many excellent references concerning sedimentary processes in tidal-deltaic areas such as southeastern Louisiana.

179. Table 4 (page 110) roughly groups the references presented in this report by subject. The most pertinent items, from a general engineering viewpoint, are shown in slanting bold face type. Although cross-referencing is not complete and the list of subjects is quite restricted, the table should provide a rough guide for literature research of a type commonly required in engineering investigations.


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Table 4

SUBJECT INDEX OF REFERENCES

| Subject | Reference Number |
|---|---|
| Pleistocene Deposits | 11, 18, 22, 23, 28, 54, 113, 114, 124, 127, 130 |
| Fluvial Deposits (Natural Levee, Point Bar, Abandoned Course, Abandoned Distributary) | 22, 23, 42, 49, 75, 88, 89, 90, 103, 107, 108, 111, 113, 114, 119, 120, 127 |
| Fluvial-Marine Deposits (Prodelta, Mudflats and Mudlumps, Intradelta, Interdistributary) | 2, 24, 25, 26, 27, 32, 34, 39, 48, 55, 64, 68, 69, 71, 80, 88, 89, 91, 92, 93, 94, 95, 102, 110, 111, 114, 116, 117, 119, 125, 127 |
| Paludal Deposits (Marsh, Swamp, Lacustrine, Tidal Channel) | 3, 7, 14, 16, 17, 19, 24, 36, 42, 48, 49, 59, 68, 73, 74, 75, 76, 77, 81, 85, 88, 89, 97, 100, 102, 103, 108, 111, 113, 114, 116, 117, 118, 119, 127, 128 |
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| Deltaic-Coastal Processes | 3, 4, 12, 13, 15, 19, 24, 25, 26, 27, 43, 45, 47, 53, 54, 55, 65, 67, 69, 70, 71, 72, 78, 81, 84, 85, 88, 89, 90, 92, 93, 103, 104, 106, 109, 110, 113, 115, 116, 117, 119, 123, 125, 129, 131, 132 |
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